THE JOURNAL
OF THE
ROYAL AERONAUTICAL SOCIETY

(FOUNDED 1897 in succession to the ANNUAL REPORTS)

Edited for the Council by J. LAURENCE PRITCHARD, Fellow

No. 183. MARCH, 1926. Vol. XXX.

NOTICES

Elections

The following members were elected at a Council Meeting held on January 5th, 1926:—

Fellow.—Mr. C. W. Tinson.

Associate Fellows.—Mr. L. G. Brazier, Squadron Leader J. A. G. de Courcy, Mr. G. H. Dowty, Mr. A. N. Jackson, Mr. G. E. Page and Dr. D. R. Pye.

Student.—Mr. N. F. Winny.

Members.—Lieutenant-Colonel J. Barrett-Lennard, Mr. H. S. Daniels, Mr. R. W. Green and Mr. S. Humphries.

The following were elected on February 16th:—

Fellows.—Mr. F. Koolhoven, Mr. C. L. Lawrance and Mr. W. O. Manning.

Associate Fellow.—Flying Officer J. Durward.

Associates.—Mr. E. Hopkins, Mr. S. S. Martin and Commander J. B. B. Tower.

Students.—Mr. E. V. Dolby, Mr. N. J. Hancock, Mr. E. C. Harvey, Mr. T. Tanner and Mr. E. T. J. Weston.

Annual General Meeting

The Annual General Meeting will be held in the Library on Thursday, March 25th, at 5.0 p.m. The Statement of Accounts for the year ending December 31st, 1925, and the Council's Annual Report will be found on page 154. of this issue.

Notice of any subject to be brought up for discussion at the meeting must be received by the Secretary not later than March 11th. Nominations for election to the vacancies on the Council, signed by two voters and accompanied by a statement signed by the Candidate signifying his willingness to serve if elected, must be received by the Secretary not later than March 6th. The following Members of Council are due to retire and are eligible for re-election:—Air Vice-Marshal Sir W. Sefton Brancker, Mr. Griffith Brewer, Professor C. Frewen Jenkin, Major A. R. Low, Mr. W. O. Manning, Mr. J. D. North, Lieutenant-Colonel A. Ogilvie, Sir Napier Shaw, Mr. H. E. Wimperis and Mr. R. McKinnon Wood.

Postponed Lecture

When it became known that Mr. Cobham would not be back by that date, Flight Lieutenant Cooch very kindly agreed to give his lecture on "Landing Aeroplanes in Fog" on February 25th. It is very much hoped that Mr. Cobham will be able to give his lecture on "Long Distance Aeroplane Flights" on Thursday, March 18th. The lecture will take place at the Royal Society of Arts, 18, John Street, Adelphi, W.C.2, at 6.30 p.m.

Special Lecture

Marchese de Pinedo, who recently flew from Italy in a Savoia seaplane to Australia and back by Japan, will read a paper to the members of this Society on his flight, at 6.30 p.m. on Thursday, April 8th, in the theatre of the Royal Society of Arts. The paper will be read in English. The title of the lecture will be "A 35,000 Miles Flight."

Tenth International Aeronautical Exhibition

La Chambre Syndicale des Industries Aéronautiques announce that the Tenth International Aeronautical Exhibition will be held in the Grand-Palais, Champs Elysées, Paris, in November and December next.

Presentations to the Library

The Council desire to acknowledge gratefully the gift of a small model of Hargrave's Rigid Stable Aeroplane, presented by his daughter, Mrs. Gray. The model was made by the author to illustrate a paper which he read before the Royal Society of N.S. Wales, and which was published in Vol. XLIII. of their Proceedings.

The Council also record their thanks to Mr. R. H. Tarleton for presenting a large selection of photographs illustrating the production of aero engines during the war.

Library Fund

The Council gratefully acknowledge the following donations to the Library Fund:—Anonymous Member, £1 1s.; Mr. David Longden, £2 2s.; Mr. C. W. Miller (U.S.A.), £1 1s.; Mr. H. G. ffiske, £2 2s.; Mr. G. Selfridge, £1 1s.; Sir J. C. G. Sykes, £1 1s.; Captain Acland, £1 1s.; Mr. H. P. Marsh, £1 1s.; Mr. F. Tymms, 14/-.

It is hoped that other members who have had their subscriptions reduced may send the balance to the Library Fund.

Coventry Branch

The inaugural lecture before the Coventry Branch of the Society will be given on March 4th by Mr. W. S. Farren, Associate Fellow, on "The Autogiro."

Students' Section Programme

Thursday, March 11th, 6.0 p.m., in the Library.—"Experimental Flying from the Pilot's Point of View," by Flying Officer R. L. Ragg.

Thursday, March 25th, **6.30** p.m., in the Library.—Lecture and Discussion, "Stalled Flying," by Mr. S. S. Hall, B.Sc., D.I.C.

Thursday, April 15th, 6.0 p.m., in the Library.—"Supercharged Aero Engines," by Mr. R. F. R. Pierce.

Will Students please note the change of time of the lecture on March 25th and that the date of the following one has been postponed to April 15th?

The visit arranged by the Students' Section to Croydon Terminal Aerodrome on February 6th was much appreciated by the members. A party of thirty was shown round the aerodrome by Captain Gillman, A.F.R.Ae.S., who made the visit an instructive and enjoyable one.

The Month's Arrangements

Thursday, March 4th, 6.30 p.m., in the Library.—"The Development of Airship Mooring and Handling," by Major G. H. Scott, C.B.E., A.F.C., A.F.R.Ae.S.

Thursday, March 11th, 6.0 p.m., in the Library.—Students' Meeting. "Experimental Flying from the Pilot's Point of View," by Flying Officer R. L. Ragg.

Tuesday, March 16th, 5.30 p.m.—Council Meeting.

Thursday, March 18th, 6.30 p.m., at the Royal Society of Arts, John Street, Adelphi, W.C.2.—"Long Distance Aeroplane Flights," by Mr. A. J. Cobham.

Thursday, March 25th, 5.0 p.m., in the Library.—Annual General Meeting.

,, ,, ,, 6.30 p.m., in the Library.—Students' Meeting. Lecture and Discussion, "Stalled Flying," by Mr. S. S. Hall, B.Sc., D.I.C.

Thursday, April 8th, 6.30 p.m., at the Royal Society of Arts, John Street, Adelphi, W.C.2.—The Marchese de Pinedo will give an account of his seaplane flight to Australia, Japan and back.

J. LAURENCE PRITCHARD,
Honorary Secretary.

ROYAL AERONAUTICAL SOCIETY

61ST ANNUAL REPORT OF THE COUNCIL, 1925-1926

Council

Chairman: Air Vice-Marshal Sir Sefton Brancker, K.C.B., A.F.C., F.R.Ae.S.
Vice-Chairman: Lieutenant-Colonel H. T. Tizard, A.F.C., F.R.Ae.S.
Griffith Brewer, Esq., F.R.Ae.S.
Wing Commander T. R. Cave-Browne-Cave, C.B.E., F.R.Ae.S.
Sir Mackenzie D. Chalmers, K.C.B., C.S.I.
C. R. Fairey, Esq., C.B.E., F.R.Ae.S.
Professor C. Frewen Jenkin, C.B.E., F.R.Ae.S.
Major A. R. Low, A.M.I.E.E., F.R.Ae.S.
W. O. Manning, Esq., A.F.R.Ae.S.
Major R. H. Mayo, O.B.E., F.R.Ae.S.
J. D. North, Esq., F.R.Ae.S.
Lieutenant-Colonel A. Ogilvie, C.B.E., F.R.Ae.S.
Lieutenant-Colonel Mervyn O'Gorman, C.B., D.Sc., F.R.Ae.S.
Colonel the Master of Sempill, A.F.C., A.F.R.Ae.S.
Sir Napier Shaw, F.R.S., D.Sc., F.R.Ae.S.
T. O. M. Sopwith, Esq., C.B.E., F.R.Ae.S.
C. W. Tinson, Esq., A.F.R.Ae.S.
H. T. Vane, Esq.
Sir Henry White-Smith, C.B.E.
Major H. E. Wimperis, O.B.E., F.R.Ae.S.
R. McKinnon Wood, Esq., A.M.Inst.C.E., F.R.Ae.S.
Honorary Treasurer: Mr. A. E. Turner.
Honorary Librarian: Mr. J. E. Hodgson.
Honorary Secretary: Mr. J. L. Pritchard, Hon.F.R.Ae.S.

Membership

The following table of the Membership position on 1st January, 1926, has been prepared, showing the state of each grade. The figures in brackets show the corresponding membership on 1st January, 1925:—

	No. of Members.	Hon. and Life Members.	Suspended.	Totals.
Fellows	59 (56)	13 (13)	— (2)	72 (71)
Associate Fellows ...	284 (265)	8 (8)	6 (20)	298 (293)
Students	62 (84)	—	8 (18)	70 (103)
Members	53 (61)	16 (15)	2 (9)	71 (85)
Associate Members ...	55 (60)	— (1)	3 (4)	58 (65)
Founder Members ...	50 (52)	—	1 (1)	51 (53)
Foreign Members ...	28 (27)	1	1 (7)	30 (34)
Scottish Branch ...	51 (51)	—	39 (39)	90 (90)
	642 (656)	38 (37)	60 (100)	740 (794)

Library

The Council again desire to thank Mr. J. E. Hodgson, the Honorary Librarian, for the valuable time which he has devoted to the Library during the year. A number of books have been added to the shelves during the year, and the Library is now one of the most valuable aeronautical libraries in the world. The Council are pleased to note that an increasing use is being made of the Library, and it is hoped that members will take a still greater advantage of the facilities for borrowing by post.

Awards

The R.38 Memorial Prize for 1925 was awarded to Mr. R. A. Frazer, B.A., B.Sc., Associate Fellow, for his paper on "The Rigid Airship in Relation to Full-Scale Experiments." The paper was published in the Journal for September, 1925.

The Society's Silver Medal for the year 1924 was awarded to Major W. S. Tucker, D.Sc., A.M.I.E.E., for his paper on "Sound Reception," which appeared in the issue of the Journal dated August, 1924.

R.38 Memorial

On 29th June, 1925, H.E. the American Ambassador (Mr. Alanson B. Houghton) unveiled the memorial in memory of the British and Americans who lost their lives in the disaster to the airship R.38 over the Humber on 24th August, 1921. A full account of the unveiling of the memorial appeared in the Journal for July, 1925.

Branches

During the year the Council have had under consideration the formation of local branches of the Society and in January they issued rules for the formation of such branches. The response has been very gratifying. The first branch to be formed, the Coventry Branch of the Royal Aeronautical Society, has already over 200 members, and applications for the formation of other branches are now under consideration. The Council feel that the formation of such branches will, ultimately, greatly stimulate interest in aeronautics and will considerably widen the scope of the Society's activities. A notice of the rules governing local branches was published in the Journal for February, 1926.

Scottish Branch

During the year the Scottish Branch has continued to be very active and its lectures have been very well attended. Much of the enthusiasm shown and the success of the branch has been due to the indefatigable Secretary, Mr. J. Buyers Black.

Students

During the year Mr. S. Scott Hall, a student at Imperial College, South Kensington, and the holder of a Busk Scholarship, together with Mr. Penrose and Mr. Shadwell Hooper, formed a small committee to revive the Students' meetings and visits. Under the able secretaryship of Mr. Scott Hall, the Student section has flourished, and a number of exceedingly well-attended visits to Croydon and various aircraft works, and lectures have been held. The Council feel strongly that co-operation among the Students in this way is of great importance for the future welfare of the Society, and they hope that the work which has been so ably revived will be continued from year to year.

Associateship

At a special General Meeting, held on 30th December, 1925, it was decided to form a new technical grade. Persons belonging to the grade will be called Associates, will receive a certificate of Associateship and will have the right to place the letters A.R.Ae.S. after their names. The new grade makes special appeal to ground engineers, inspectors and examiners of aeronautical materials, those holding a pilot's "B" licence, those holding a navigator's certificate, those who have commissioned or warrant rank in the general duties branch of the Royal Air Force, and those who have held a position equivalent to foreman for a period of not less than three years.

The members of this grade have the usual privileges of members and the annual subscription has been fixed at only £1 1s. 0d. without the Journal and

£2 2s. 0d. with it, no entrance fee being imposed for those who join during 1926, though the Council may impose an entrance fee after 31st December, 1926.

New Rules

At a special General Meeting held on 30th December 1925, the rules of the Society were altered, particularly with regard to the formation of the new grade of Associateship. A copy of the new rules is now in the hands of the printers.

Subscriptions

At the special General Meeting held on 30th December, 1925, it was decided to lower the subscriptions and to make them more uniform.

Journal

The Council are again able to record a continued improvement in the circulation of the Journal and other publications to persons outside the membership of the Society.

Lecture Programme

1925.

Oct. 1st.—Air Vice-Marshal Sir W. S. Brancker, "The Technical Lessons of Six Years of Air Transport."

Oct. 15th.—Major C. K. Cochran-Patrick, "Aircraft Survey in Burma."

Oct. 22nd.—Senor de la Cierva, "The Auto-Gyro."

Oct. 29th.—Mr. W. L. Cowley, "Aircraft Transport Economy."

Nov. 3rd.—Wing Commander T. R. Cave-Browne-Cave, "The Evaporative Cooling of Aero Engines and Condensation of their Exhaust Gas." Joint meeting with the Institution of Automobile Engineers.

Nov. 12th.—Mr. H. B. Howard, "Some Problems in Aeroplane Structural Design."

Nov. 26th.—Mr. A. H. R. Fedden, "Installation Problems in Air-Cooled Engines."

Dec. 3rd.— Professor B. Melvill Jones, "The Control of Stalled Aeroplanes."

1926.

Jan. 7th.—Professor A. J. Sutton-Pippard, D.Sc., F.R.Ae.S., "The Experimental Stress Analysis of Frameworks, with Special Reference to the Problems of Airship Design."

Jan. 21st.—Major J. S. Buchanan, A.F.R.Ae.S., "The Schneider Cup Race, 1925."

Feb. 4th.—Mr. C. L. Lawrance, "American Aircraft Engine Development." Joint meeting with the Institution of Automobile Engineers.

Feb. 25th.—Flight Lieutenant H. Cooch, "Landing Aeroplanes in Fog."

Mar. 4th.—Major G. H. Scott, C.B.E., A.F.C., A.F.R.Ae.S., "The Development of Airship Mooring and Handling."

Mar. 18th.—Mr. A. J. Cobham, "Long Distance Aeroplane Flights."

April 22nd.—Captain G. T. R. Hill, A.F.R.Ae.S., "The Tailless Aeroplane."

April 29th.—Lieutenant-Colonel V. C. Richmond, O.B.E., A.F.R.Ae.S., "The Results of Recent Airship Flight Tests."

Wright Memorial Lecture

The Thirteenth Wilbur Wright Memorial Lecture was delivered on April 30th, 1925, when Commander J. C. Hunsaker read a paper by Rear-Admiral D. W. Taylor on "Some Aspects of the Comparison of Model and Full Scale Tests."

Conversazione

Following on the suggestion of Lieutenant-Colonel Lockwood Marsh that the 60th anniversary of the foundation of the Society should be commemorated in some form, the Council arranged a Conversazione, which was held at the

Science Museum, South Kensington, on 12th January, 1926. A full account of the Conversazione, which was attended by a large number of the Society's members and their guests, appeared in the Journal for February, 1926. Much of its success was due to Colonel the Master of Sempill, who kindly undertook all the necessary organisation.

Finance

The Council have to report that there is an excess of income over expenditure for the first time since the Great War. Not only has a balance been shown, but the outstanding printing bill has been reduced by £478 14s. 0d., and it is hoped that during the coming year the bill will be paid up to date. This satisfactory state of affairs has been brought about by economies in administration effected by the Society, by improvement in the revenue from advertisements in the Journal, and finally by donations of £250 each from the Air Ministry and the Society of British Aircraft Constructors.

Endowment Fund

At the Conversazione there was inaugurated an appeal for an Endowment Fund to place the finances of the Society on a satisfactory and permanent basis. The Council desire to draw particular attention to this fund. It is of the utmost importance, in view of the formation of branches and the formation of the new technical grade of Associateship, with the consequent necessary increase of expenditure, that a fund of this kind should be well supported. It is hoped that members of the Society will exert every possible effort during the coming year to make the Endowment Fund a success.

Lieutenant-Colonel W. Lockwood-Marsh

The Council wish to place on record their great appreciation of the valuable services rendered to the Society by Lieutenant-Colonel W. Lockwood Marsh. Colonel Marsh was secretary during the difficult financial years following the Great War, and it was very largely due to his energy that the Society was able to weather as well as it did the consequent falling off in its membership.

It was with great regret that the Council felt it their duty, after a careful consideration of the financial position, to accept the offer of Colonel Marsh to resign so that further economies could be made in office salaries.

Honorary Treasurer

The Council, for the sixth year in succession, wish to express their appreciation of the advice and assistance received from Mr. A. E. Turner, who has continued to act as Honorary Treasurer.

Honorary Secretary

On 1st May, 1926, Mr. J. Laurence Pritchard, the Editor, kindly consented to act as Honorary Secretary of the Society until such time as a permanent Secretary could be appointed. The Council wish to express their appreciation of the services and time which he has given to the Society since he has taken up his duties.

Staff

The Council have pleasure in recording their great appreciation of the services of the staff, Miss O. St. Barbe and Miss Barwood. On Miss O. St. Barbe, the Assistant Secretary, has fallen a greater burden than in past years, and the Council wish to thank her for the assistance she has given the Honorary Secretary.

AERIAL SCIENCE, LIMITED

Balance Sheet,

Dr.	£ s. d.	£ s. d.
To *Nominal Capital*—		
Divided into 20 shares of 1/- each and 999 shares of £1 each	1000 0 0	
.. *Capital Issued and Paid Up*—		
19 shares of 1/- each		19 0
.. *Sundry Creditors*		788 11 1
.. *Subscriptions Received in Advance*		71 17 0
.. *Carnegie U.K. Trust Grant*—		
For Purchase of Books		500 0 0
Expended to 31st December, 1924	465 8 7	
.. *Donation Earmarked for Endowment Fund*		50 0 0
.. *Reserve Fund*—		
Entrance Fees and Life Compositions of present members, as at 31st December, 1924	2750 14 0	
Receipts for year to 31st December, 1925	81 18 0	
	2832 12 0	
Deduct Income and Expenditure Account Deficiency at 31st December, 1924 ... 2182 1 2		
Less Excess of Income over Expenditure for year to 31st December, 1925 ... ... 409 12 2		
	1772 9 0	
		1060 3 0
		£2471 10 1

We report to the Shareholders that we have examined the Books of the Society and have obtained put upon the outstanding subscriptions. Subject to this remark we are of opinion that such Balance affairs according to the best of our information and the explanations given to us and as shown by

3, Frederick's Place,
Old Jewry, E.C.2.
17th February, 1926.

Income and Expenditure Account

Dr.	£ s. d.
To Office Rental, Lighting and Insurance	332 2 0
.. Salaries	771 16 2
.. Printing and Stationery	94 15 3
.. Postage	72 17 6
.. Library Expenses	15 19 0
.. Office Expenses	70 18 1
.. Meetings	52 19 1
.. Journals, Pamphlets, Etc.	210 7 10
.. Audit Fee	17 17 0
.. Income Tax	10 2 6
.. Sundries	18 2 6
.. 60th Birthday Celebrations	12 14 6
.. Subscriptions Written Off	203 16 6
.. Balance, being Excess of Income over Expenditure	409 12 2
	£2294 0 1

Journal and Sundry Publications Trading

	£ s. d.
To Stock, 31st December, 1924	454 8 3
.. Law Costs (Advts.)	3 3 0
.. Refund of Journal Subscription	1 7 6
.. Purchase of old Journals	4 0 0
.. Printing of Journal	734 4 2
.. Postage of Journal	78 17 8
.. Binding of Journal	6 16 6
.. Blocks for the Journal	310 4 0
.. Printing of Advance Proofs	65 3 6
.. Printing of Reprints	44 7 6
	£1702 12 1

(The Royal Aeronautical Society).

31st December, 1925

Cr.	£ s. d.	£ s. d.
By *Office Furniture, Printed Books, Bindings, Stationery, Old Prints, Etc.*—		
As at 31st December, 1924 (including Carnegie Grant £465 8s. 7d.)		803 3 6
,, *Stock of Journals, Etc.*		396 7 1
,, *Stock of Stationery*		5 2 0
,, *Sundry Debtors* (including Subscriptions owing)		155 2 11
,, *Investment at Cost*—		
£786 3s. 0d. 5% War Stock (Inscribed), 1929/47 ...		725 13 6
,, *Cash at Bank*—		
On Current Account	185 16 7	
On Deposit Account	200 0 0	
Cash in Hand	4 6	
		386 1 1
		£2471 10 1

all the information and explanations we have required. We are not in a position to judge of the value Sheet is properly drawn up so as to exhibit a true and correct view of the state of the Society's the Books of the Society.

(Signed) PRICE, WATERHOUSE & CO.

for the Year to December 31st, 1925

Cr.	£ s. d.	£ s. d.
By Annual Subscriptions		1746 18 4
,, Interest on Investment	39 3 2	
,, Interest on Deposit Account	7 18 7	
		47 1 9
,, Donations Received	550 0 0	
Less Earmarked for Endowment Fund	50 0 0	
		500 0 0
		£2294 0 1

Account (Secretary's Statement)

	£ s. d.
By Sale of Journals	579 12 5
,, Advertising Revenue	411 16 4
,, Journal Binding	7 7 0
,, Sale of Advance Proofs	18 5 2
,, Sale of Sundry Publications	78 16 3
,, Stock, 31st December, 1925	396 7 1
,, Balance, loss carried to Income and Expenditure Account	210 7 10
	£1702 12 1

PROCEEDINGS

FOURTH MEETING, FIRST HALF, 61ST SESSION

A meeting of the Royal Aeronautical Society was held in the Society's Library at 7, Albemarle Street, London, on Thursday, October 29th, 1925, when a paper on "Aircraft Transport Economy" was read by Mr. W. L. Cowley.

Air Vice-Marshal Sir W. SEFTON BRANCKER, Chairman of the Society, presided, and in introducing the lecturer said: I have to introduce to you to-night Mr. Cowley, who is a new recruit in the investigation of air transport problems. He has made a study of technical problems of air transport, and is attached to the Air Transport Sub-Committee of the Aeronautical Research Committee. He commenced studying the question of air transport practically by taking several journeys by air from Croydon, and spending six months at Martlesham seeing machines tested. He represents an endeavour to bring science and research into close and constant touch with the endless demands of actual operations.

Mr. COWLEY, before reading an abstract of his paper, said: I was very pleased to hear Sir Sefton Brancker was to be Chairman of this meeting, because I think he is one of the best possible chairmen for a discussion on the subject of air transport economy. I think you will all agree with me that no one has worked harder than he has for air transport.

I have often heard him say that the first to design a really successful commercial machine would have the monopoly of a large world market. I sincerely hope that this paper and the discussion thereon will assist in the attainment of the much-desired machine, through making a study of the commercial factors with which we are concerned.

AIRCRAFT TRANSPORT ECONOMY

BY W. L. COWLEY, A.R.C.SC., D.I.C., WH.SC.

In 1922 the Civil Aviation Advisory Board to the Air Ministry published its first report* in which it recommended to His Majesty's Government that "A Technical and Scientific Investigation should be instituted to ascertain the most suitable type or types of aircraft and engines for a service to India and the most economic length of the stages," and that this investigation should be carried out by a specially appointed Sub-Committee of the Aeronautical Research Committee. The outcome of this was the formation of the "Air Transport Sub-Committee" and it is upon part of the work of this Committee that the present paper has been evolved.

On examining the terms of reference of the Sub-Committee, viz., §12 of the report mentioned above, it will be seen that its activities cover a very extensive field and, before satisfactory answers can be given to many of the questions involved, a complete study must be made of costs and of the economical relationship that exists between the various factors concerned.

Selection of Economic Data

The subject of economy in aerial transport, unfortunately, is greatly handicapped by the lack of reliable data. Experience in other forms of transport

* First Report on Imperial Air Mail Services by the "Civil Aviation Advisory Board," published by H.M. Stationery Office.

might help to a small extent, but the problems of the air are so fundamentally different from those usually met with, that conclusions derived from this experience, if only used in a general way, are liable to be very misleading if not to obscure the points at issue completely. The very limited data that exists on commercial aircraft are in many cases derived from military experience, and military requirements are often in direct opposition to those of civil work. Thus, although very high speed, good climbing ability, a high ceiling, manœuvrability and even a clear field of view for the crew would appear to be important features of an aeroplane from a military standpoint, they become of secondary importance in civil craft compared with safety, reliability and carrying capacity, and it is only in one class of military machine, viz., the bombing machine, that anything approaching a parallel case can be found.

The most useful information on costs is the data accumulated by the very limited number of air transport companies that have operated over a few years, but it must be understood that most of these statistics are of a private nature and very little has been published by the companies concerned. Moreover, their machines, as previously mentioned, have been, in the main, growths from the military side and even now these companies are making great changes in their machine types. It follows, therefore, on the one hand, that investigations carried out with such data as a basis might lose their value as aerial transport develops, but, on the other hand, a useful purpose will be served if they can indicate the direction in which this advancement should be made.

Data obtained from both military and civil sources have been accumulated in the report by the Civil Aviation Advisory Board and used in the estimates made of the capital and running costs of the several stages in a proposed London to India Air Mail Service. These data are the most comprehensive published and will be used as a basis for all economical investigations in this paper.

For present purposes the most suitable figures of the report are those given in Appendix I. (*a*), viz., those for a proposed service of one machine a day each way on a London-Brussels-Constantinople route. The figures are reproduced in Table 1. In brackets are given modified figures allowing for the reduction in the cost of petrol from 3s. to 1s. 6d. per gallon. Items such as depreciation seem high in this table, but no alteration can be made with confidence at present, other than the one for petrol costs, without seriously affecting the balance of the table.

TABLE 1.

LONDON-BRUSSELS-CONSTANTINOPLE.

(Taken from Appendix I. (*a*) Report on Imperial Mail Services.)

GENERAL REQUIREMENTS.

(1) Service.—London-Brussels-Constantinople.
(2) Sub-Stations.—London.

	Miles.
Brussels	200
Frankfort	200
Nuremburg	110
Vienna	270
Budapest	150
Bucharest	390
Constantinople	280
	1,600

(3) Mileage.—1,600.
(4) Frequency.—Daily service; one machine each way per day.
(5) Type of machine and engine.—Landplane; 100 m.p.h. cruising speed at 5,000ft.; 3½ hours petrol capacity; 2,000lb. load exclusive of pilot; 400/450 h.p. engine.

CAPITAL COST.

	£
(1) Machines, 17 at £4,000	68,000
(2) Engines, 17 at £2,500	42,500
(3) Spare engines, 6 at £2,500	15,000
(4) Spares for machines and engines	11,000
(5) Transport vehicles	7,000
(6) Freight and passages of personnel to bases	2,000
(7) Working capital	20,000
	£165,500

RUNNING EXPENSES AND UPKEEP—PERIOD, ONE YEAR.

(1) FUEL.

Petrol.

Total hours, say	11,700
Consumption per hour	25 gallons
Price per gallon	3/- (1/6)

Cost £43,875 (£21,937).

Oil.

Consumption per hour	1½ gallons
Price per gallon	7/6

Cost £6,582.

Total cost of fuel £50,457 (£28,519).

(2) STAFF.

	£
General manager	2,000
One chief engineer	1,000
Three assistant managers at £800	2,400
24 pilots (£300 and £1 per hour)	18,900
One assistant engineer	800
Medical attendants	1,000
36 mechanics at £300	10,800
Labour	2,000
Office Staff.	
Two clerks at £300	600
Two clerks at £200	400
	£39,900

(3) RENEWALS, REPAIRS AND UPKEEP.

Replacements of spaces, 100 per cent. ...	11,000
Rent	1,000
Hired transport	5,000
Power, light, etc.	1,000
	£18,000

Passenger's Fare 100%
Running Costs 40·9%
Overhead charges 53·8%
Interest 5·3%
Fuel & Oil 15·25%
Depreciation & Repairs 25·65%
Staff 21·35%
Insurance 19·65%
Sundries 12·8%
Interest 5·3%
15·25% Fuel and Oil.
25·65% Depreciation and Repairs.
10·1% Pilots' Staff.
5·78% Mechanics & Labour Staff.
5·47% Management Staff.
19·65% Insurance.
12·8% Sundries (housing & landing fees etc.)
5·3% Interest on Capital.

FIG. 1.

(4) Depreciation.

33⅓ per cent. on 17 planes	22,666
25 per cent. on 23 engines	14,375
	£37,041

(5) Insurance.

Aircraft; all risks (£110,500 at 25 per cent.)	27,625
Equipment (say £154,000 at 5 per cent.) ...	7,700
Pilot's insurance (24 pilots at £1,000, 6 per cent)	1,440
	£36,765
(6) Landing and Housing Fees	7,000
(7) Sundry Expenses (including general expenses, publicity, advertising, detention and travelling allowances)	10,000

Total £199,163 (£177,230).

Summary.

Initial capital £165,500

Expenses.

	£
(1) Overhead charges (*i.e.*, staff, rent, hired transport, power, light, housing and landing fees, insurance and sundries)	100,665
(2) Running costs (*i.e.*, petrol, oil, depreciation and replacements)	98,498 (£76,561)
(3) Interest at 6 per cent.	9,930
	£209,093 (£187,155)
Cost per daily trip per machine	£286 9 0 £256 8 0)
Hours per trip	16
Miles per trip	1,600
Average speed in miles per hour	100
Cost per flying hour per machine	£17 18 8 (£16 0 6)
Cost per machine mile	3/7 (3/2½)

This table is represented in graphical form in Fig. 1, where the broad band indicates the passengers' fare or the income, and the division of the band shows the proportions into which this is broken up to pay the costs of the various items indicated. The total width of the bands at any sub-division is constant.

Effect on Economy of the Seasonal Variation in Traffic

The estimates from which Fig. 1 was obtained were based upon a uniform traffic throughout the year. For air lines in the British Isles or to the Continent the traffic is greatly interfered with by weather and during the winter months it falls sometimes to as low a figure as 15 per cent. of the maximum summer traffic. Fig. 2 shows the monthly variation of the total number of British aircraft arriving from or departing for the Continent from October, 1919, to October, 1923.

On the same diagram is plotted the number of flights per month of a fleet of four machines for eleven months, October to August inclusive. The law of variation in both cases is roughly the same.

Monthly Variation of Traffic

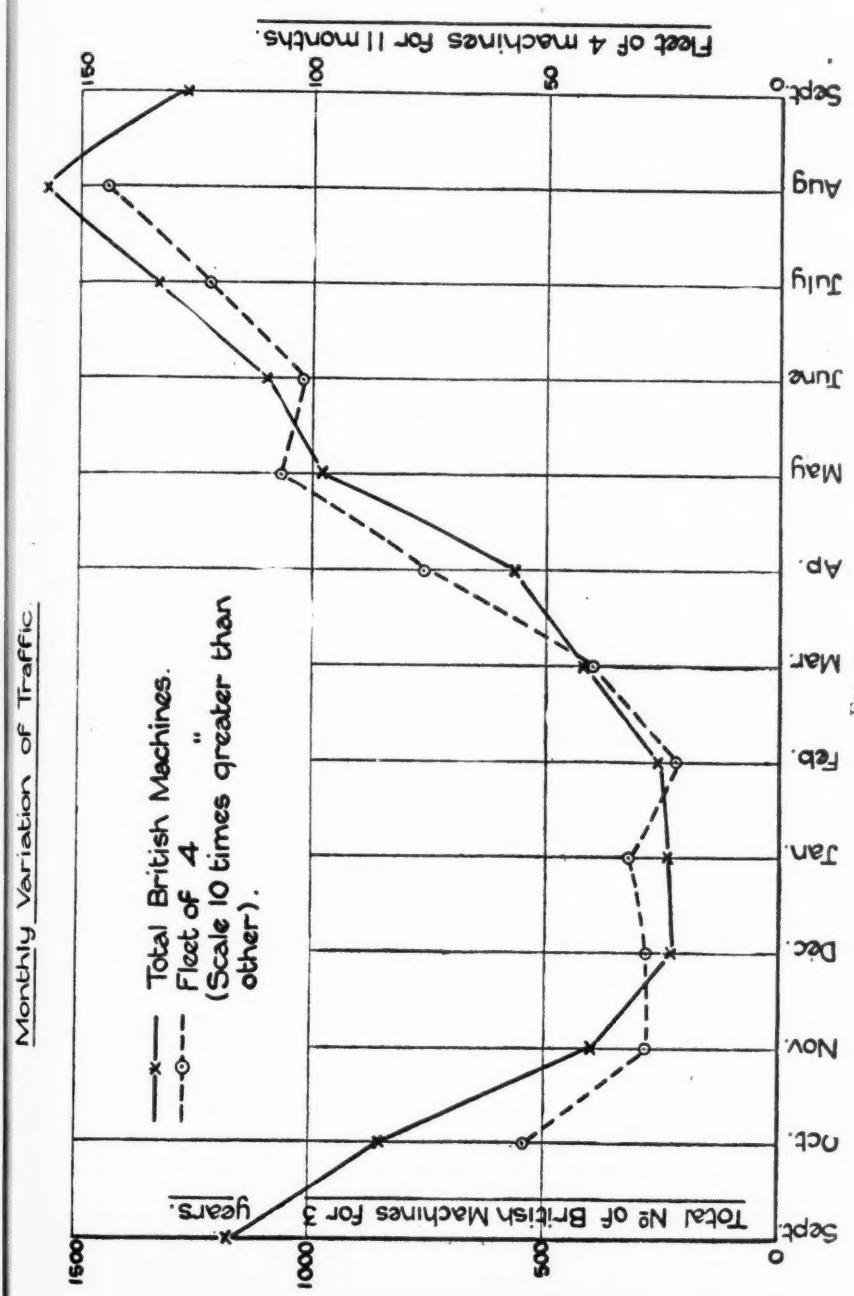

Monthly Variation of Traffic.
Total British Machines.
Fleet of 4
(Scale 10 times greater than other).
Total N° of British Machines for 3 years.
Fleet of 4 machines for 11 months.
1500
1000
500
0
150
100
50
0
Sept.
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Ap.
May
June
July
Aug
Sept.

FIG. 2.

TABLE 2.

FLEET OF FOUR AEROPLANES.

Month.	No. of Flights.	Mileage per month.	Passenger miles (approx.).	Percentage of average. Flying charges per mile flown.*	Operating salaries and wages.	Depreciation.	Insurance.	Overhauls.	Total commercial charges.	Cost. per Passenger mile. †
Oct.	53	12,190	107,000	110	116	102	124	98	132	138
Nov.	28	6,440	42,200	114	98	102	115	128	94	276
Dec.	28	6,440	39,300	108	84	103	113	93	107	288
Jan.	32	7,360	26,500	106	83	102	115	37	85	267
Feb.	22	5,060	30,500	98	80	104	115	61	96	334
Mar.	40	9,200	69,400	101	87	104	115	113	108	176
April	77	17,710	150,000	102	120	105	113	144	96	98
May	107	24,610	123,000	99	78	97	−122‡	193	90	63.3
June	103	23,690	176,000	102	109	102	84	87	87	80.3
July	121	27,830	269,000	98	130	105	266§	66	97	66.1
Aug.	143	32,890	332,000	92	115	74	62	78	108	46
Total item as percentage of total cost				22.8%	21.4%	12.2%	9.4%	8.4%	25.8%	

It is to be expected that this variation of traffic would have an appreciable effect upon the economic figures given in Table 1 and Fig. 1. Whether, or not, this is the case may be seen by referring to Table 2, where the costs, tabulated in a slightly different manner from those of Table 1, are given for the four machines mentioned above. The columns of this table show how the various items change from month to month and the figures given are expressed as percentages of the average for the eleven months. At the feet of six columns are given the total costs of the items for the full period as percentages of the total expenditure. These expenses can be compared directly with the corresponding items in Table 1, by adding together depreciation and overhauls; the figures concerned are given in Table 3.

TABLE 3.

COMPARISON BETWEEN ESTIMATES IN TABLE 1 WITH ACTUAL COSTS GIVEN IN TABLE 2 FOR ELEVEN MONTHS WORKING OF FOUR MACHINES.

	Table 1.	Table 2.
Fuel and Oil	15.25 per cent.	22.8 per cent.
Salaries	21.35 ,, ,,	21.4 ,, ,,
Depreciation and Repairs	25.65 ,, ,,	20.6 ,, ,,
Insurance	19.65 ,, ,,	9.4 ,, ,,
Sundries and Interest ...	18.1 ,, ,,	25.8 ,, ,,

The differences between the two columns of Table 3 are due to differences between the types of machines used as well as the monthly variation in traffic, but the latter would be chiefly instrumental in bringing about the variation

* Average is total cost ÷ total miles flown.
† Adjusting rebate on premiums.
‡ Average is total cost ÷ total passenger miles.
§ Increase due to total premium charged as claim made.

shown. Thus during the winter months machines would be running with partial load so that more flights must be made to carry the same total yearly traffic and the fuel bill would consequently increase. The insurance on the other hand chiefly depends upon the total yearly flights and should therefore remain about the same in both cases for the same yearly traffic, but, as the total costs for a line carrying a varying traffic would be higher than one carrying a uniform traffic, the insurance costs expressed as a percentage of the total costs would decrease. Table 3, therefore, might be regarded as representing approximately the effect of the variation in traffic indicated by Fig. 2. The accuracy of the figures is not sufficient, however, to allow detailed calculations to be based upon them.

It is important to notice that the cost per passenger mile given in the last column of Table 2 is about seven times as great during February as it is in August and that the falling off of traffic during the winter causes the average cost per passenger mile to become more than twice as great as the cost for August alone, that is, 8½d. instead of 4d. This comparison shows the great economic value of any improvements in operation that would lessen the traffic variation throughout the year, such as those leading to safe flight and landing in fogs and bad weather, or a grading in the scale of charges throughout the year, as, for example, decreasing the fares for winter traffic.

Relation Between Machine Size and Effects of Traffic Variation

It might be thought that, with such a high fluctuation in traffic, greater economy would result from using a large number of small machines than a few large machines which take the same total traffic, because, under such conditions, each machine used would be nearly fully loaded at any period of the year and those not required could be placed in store. An inspection of the columns of Table 2, however, shows that most of the costs, such as those for overhauls, insurance and depreciation, do not vary regularly with the variation in traffic and only about 23 per cent. of the costs, viz., flying charges, are appreciably affected by this question.

The relative economy of the large and small machines may be compared as follows:—From Table 2 it might be assumed that the flying charges are proportional to machine mileage. If now it be supposed that the economy of the line is unaffected by the size of the aeroplanes used except from the saving that can be brought about by cutting down the number of flights during slack periods, it follows that about 23 per cent. of the costs could be cut down to 1/6th of this figure during winter, viz., 4 per cent. by the saving in petrol. The average saving during the year would amount to about 10 per cent. of the total costs through substituting the smaller machines.

On the other hand, however, the multiplication of machines would demand a larger pilot staff with consequent increase in expense. To take full advantage of the petrol economy at least six small machines must be substituted for each large machine and this means multiplying the pilots' duties by six if one pilot is taken per machine or by three if it be supposed that two pilots are required for the large machines. Thus the increase in the salary bill would be 50 or 20 per cent. of the total expenses for the respective cases (see Table 1). Even taking the most favourable conditions for the small machines, viz., the case in which two pilots are used on large machines, it follows that considerable loss would result from using small machines apart from the other questions of economy. This loss is further accentuated by the fact that the ratio between the total weight of the pilots to the total commercial load carried would be greater in the case of the small machines than in the case of large machines. It appears, therefore, that no advantage would result from multiplying the number of machines, at least as far as the evidence of Table 2 is concerned.

The Most Economical Size of Machine

To determine the most economical size of machine it is necessary to study the way in which the commercial load varies with the total weight of the machine and the effect upon costs.

The manner in which the commercial load of a machine alters with size will depend chiefly upon the variation in the three factors (A) structural weight, (B) engine weight and (C) body resistance. The power, etc., it might be assumed, will be fixed by the resulting total weight and by the minimum performance requirements of the machine. A brief study of the three factors above will now be made.

(A) *Structural Weight.*—Structural weights differ considerably between the various designs of modern aeroplanes. Theoretically, from stress considerations, the ratio between the weight of a given structural design and the load carried should be greater with a heavy than with a light load, but in complicated structures such as an aeroplane, many parts are not designed for stress requirements alone, and fittings, etc., that are adequate for a large size machine are often unsuitable in form for a smaller scale design.

An interesting analysis of statistics has been made by Professor A. J. Sutton Pippard* upon the weight of the structural members of an aeroplane. For machines of the fighter class he found that the ratio of the structural weight to total weight was

$$p = 0.155 + 0.0235\,F \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and for bombing machines

$$p = 0.14 + 0.05\,F \quad . \quad . \quad . \quad . \quad . \quad (2)$$

where F is the load factor used in design, that is, the ratio between the load the machine is designed to carry and the load that would produce structural failure.

The load factor of the fighting machines from which the formula was deduced was 7 and for the bombing machines 4. Thus the design of about 50 per cent. of the total structure weight of a fighting machine and of about 40 per cent. of a bombing machine is unaffected by stress considerations. It might be assumed, therefore, that only about 60 per cent. of the structure weight of a commercial machine is directly affected by stress considerations.

In the formulæ suggested by Professor Pippard it would appear that the ratio between the structure weight and the total all-up weight is independent of the machine size, but depends only upon the type and load factor unless the difference between the fighter and bomber is in reality an effect of machine size. To test whether this is the case the weight per square foot of the wings of several British built aircraft have been plotted in Fig. 3, and a wing loading base, various ranges of total machine weight being represented by differently marked points. The wing loading was taken as abscissa as it might be expected that the wing structure weight would be greatly influenced by this factor. An inspection of the diagram, however, shows that the all-up weight does not affect the structure weight in a systematic manner. The points in the diagram break up into two systems, (*a*) single-engined machines and (*b*) multi-engined machines, and each set can be represented fairly accurately by a straight line through the origin. If it be assumed that the wing area is proportional to the total weight, the straight lines given in Fig. 3 serve to show agreement with Professor Pippard's formulæ except that in this instance discrimination has been made between single and multi-engined and not between fighting and bombing machines.

In Figs. 4 and 5 the structure weight ratio as a percentage of the total weight is given for the fuselage and alighting gear respectively for the single-engined machine. This ratio, it will be seen, fluctuates considerably, the former

* "The Effect of a Variation in Load Factor Upon Structural Weight and Performance of an Aeroplane." By A. J. S. Pippard, M.B.E., D.Sc.

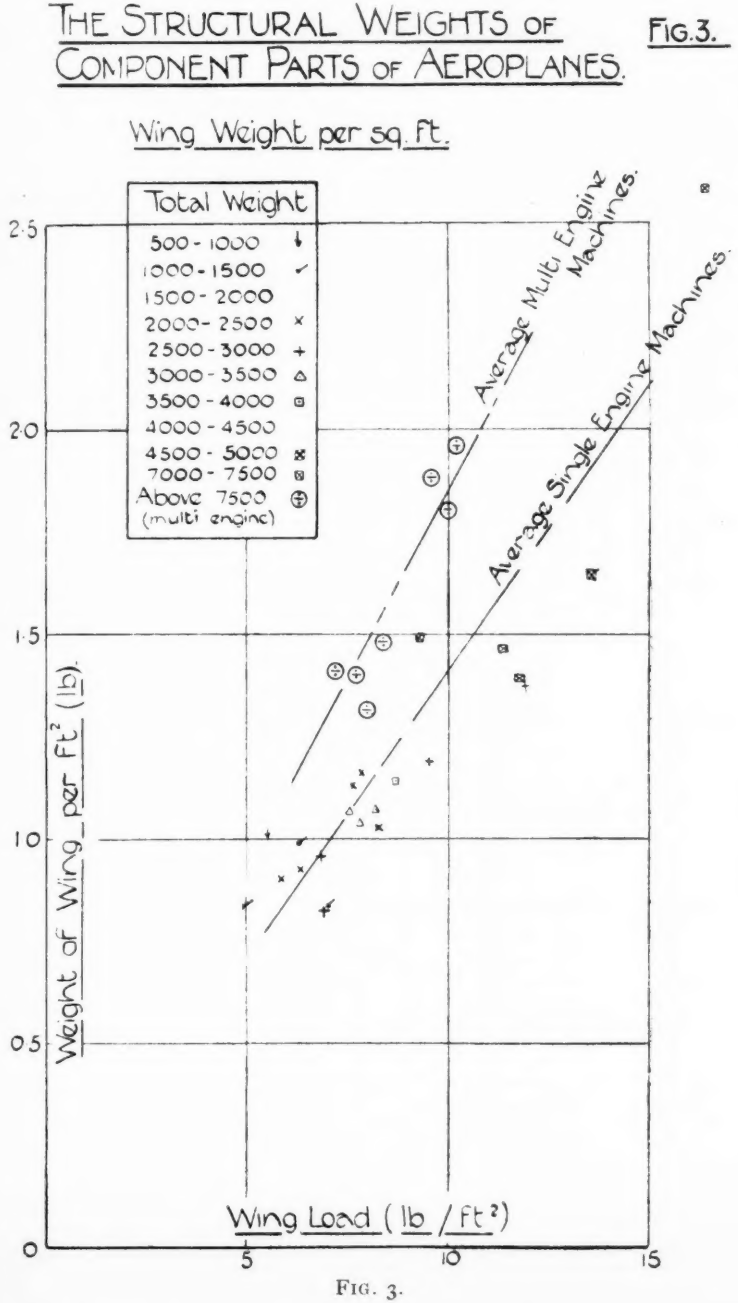

THE STRUCTURAL WEIGHTS OF COMPONENT PARTS OF AEROPLANES.
FIG.3.
Wing Weight per sq. ft.
Total Weight
500 - 1000
1000 - 1500
1500 - 2000
2000 - 2500
2500 - 3000
3000 - 3500
3500 - 4000
4000 - 4500
4500 - 5000
7000 - 7500
Above 7500 (multi engine)
Average Multi Engine Machines.
Average Single Engine Machines.
Weight of Wing per Ft² (lb).
Wing Load (lb / ft²)
2·5
2·0
1·5
1·0
0·5
0
5
10
15

FIG. 3.

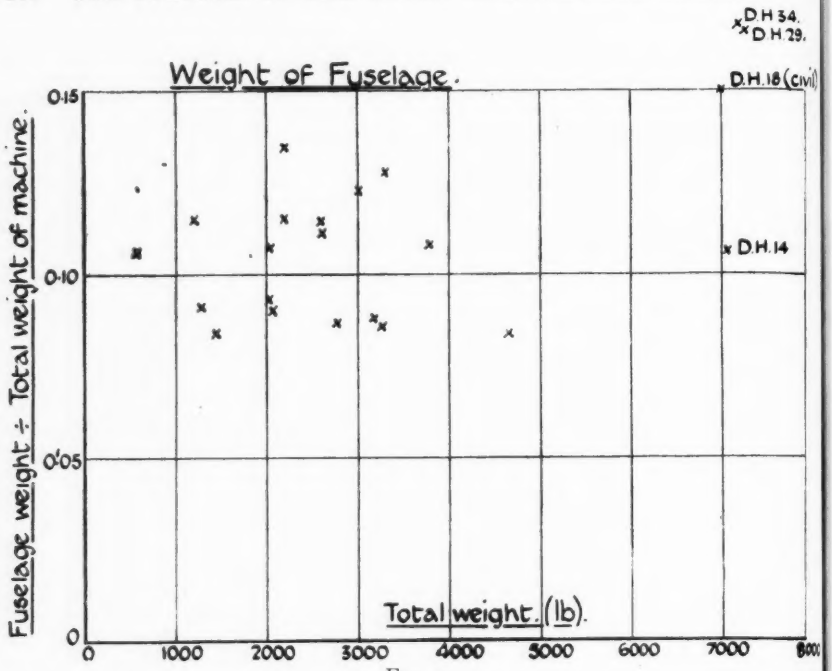


FIG. 4.
The Structural Weights of Component Parts of Aeroplanes.

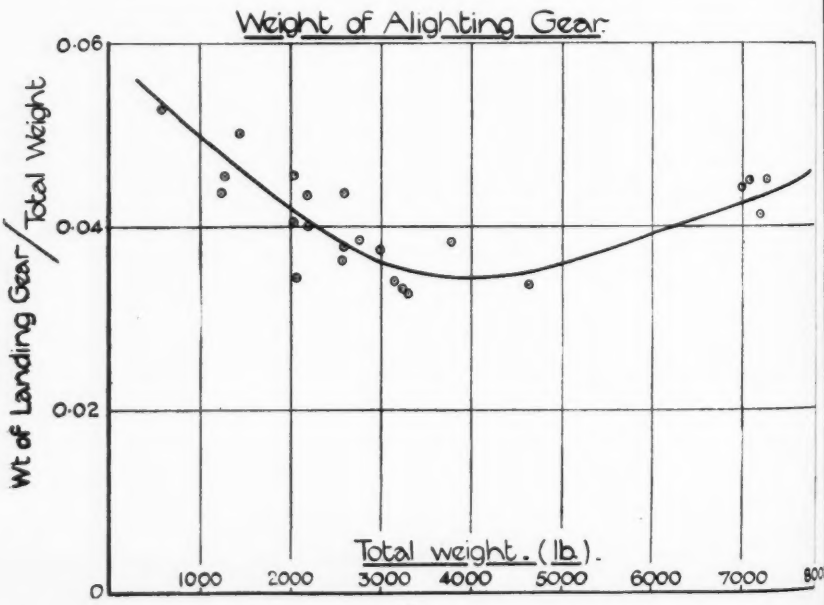


FIG. 5.
The Structural Weights of Component Parts of Aeroplanes.

varying from about 0.10 on the average for small machines to 0.15 for large machines, but the upper limit is only defined by a very few points. There appears to be a more systematic law of variation for the landing gear, but it is not of sufficient regularity to justify the use of anything more than an average overall figure for all sizes of machines.

Although little or no variation in structural weight ratio with machine size is indicated by the weight lists of typical aeroplanes, it might prove useful to investigate how this ratio should vary from stress consideration because the absence of systematic variation in the weight lists may be due to the effects of variation in type of construction, etc., outweighing those due to the increase in the size of the aircraft.

Professor Pippard in the paper referred to studies this problem by regarding the size of the machine and therefore the lengths of the members as fixed, so that only the cross sections of the members were allowed to vary. This method was necessary as he was concerned primarily with the effect of change in load factor. The dissection of the weight lists was the channel through which the constancy of the weight ratio appeared in the formulæ. In the present instance the effect of alteration in the length of the members due to the increase in the size of the machine must be studied.

For the purposes of comparison it is necessary to assume that all structures are similar so that the lengths of the members are proportional to the size of the structure, but the cross section may vary to meet strength requirements.

An inspection of Professor Pippard's paper shows that the stress relations in aeroplane structures to all practical purposes follow the three laws—

(*a*) Ribs

$$P = fA \quad . \quad . \quad . \quad . \quad . \quad . \quad (3)$$

(*b*) Struts

$$P = \pi^2 (EI/L^2) \quad . \quad . \quad . \quad . \quad . \quad (4)$$

(*c*) Beams

$$B.M. = PL = f(I/y) \quad . \quad . \quad . \quad . \quad . \quad (5)$$

where

P = load carried in any member.
A = cross sectional area.
L = length of member.
I = moment of inertia of section about neutral axis.
F = depth of section.
E = Young's modulus.
f = stress in material.

Now the design restriction upon the spar amounts to making the spar or rib depth proportional to L the linear scale of the structure, so that I becomes proportional to AL^2 and I/y to AL. For cases where no design limitations are imposed, the cross sectional area can be made similar in both cases and the same proportions would hold. Thus, if w is the weight of the member, w will vary as AL, assuming the density of the material the same, and the three relations above under all conditions will give

$$P \text{ varies as } f(w/L) \quad . \quad . \quad . \quad . \quad . \quad (6)$$

The force P will vary as the total weight of the machine and as L^2. Thus, for each member

$$f \times w \text{ varies as } W^{3/2} \quad . \quad . \quad . \quad . \quad . \quad (7)$$

where W is the total weight of the machine.

With a constant factor of safety, f will be constant so that the parts designed directly from stress considerations will increase in weight by the law

$$w \text{ varies as } W^{3/2} \quad . \quad . \quad . \quad . \quad . \quad (8)$$

The fact that the weight ratio is fairly constant in actual design might be due to the smaller load factors to which the larger machines are designed. It is clear that the load factor cannot decrease indefinitely with machine size, and if ultimately this factor remains constant, the structure weight ratio, if the stress law held, would tend to become very large.

Difference in the type of the structure design plays an important part in the weight ratios. In many of the smaller machines the tendency is to reduce head resistance by decreasing the number of interplane struts, and this probably increases the structure weight ratio. The question of the most economical spacing of these struts is receiving attention by the Air Transport Sub-Committee and an extensive programme of work upon the theory of aeroplane structures is being mapped out for investigation at the National Physical Laboratory. It is possible that considerable gain might result from other modifications such as reducing stress by a judicious initial stress distribution brought about by tightening up various wires in the structure.

The whole problem is very complex, especially in view of the fact that many other factors enter into the question to obscure the issue. Statistics on the weights of aeroplane components certainly show that the theoretical laws deduced are not borne out in practice even in a general way. An interesting case is that of the weight of the wing structure of multi-engined machines. In view of the fact that the load of such machines is more economically distributed along the span, it might be expected that the structure weight ratio of such machines should be smaller than for single-engined machines instead of the reverse as is actually found. The explanation of this might be that the increase is a consequence of the increased size of the machine as all such machines are of large design. On the other hand, it may be that to support the engines on the wings additional members must be introduced whose weight more than counterbalances the gain in weight that would otherwise occur.

It is important to note on the general question of the variation of structure weight with size of machine that in large structures it is easier to cut down weight by fairing off superfluous material than in small designs where this procedure would prove very tedious and expensive.

For the purposes of economic calculations, it may be assumed that the structure weight ratio is independent of machine size and that the ratios into which the chief parts of the structure weight is divided may be taken as 14 per cent., 13 per cent. and 4 per cent. of the total weight for wings, fuselage and landing gear for single-engined machines, and 18 per cent., 11 per cent. and 4 per cent. for multi-engined machines. These values give fairly good agreement with Figs. 3, 4 and 5, and agree fairly well for the total structural weight ratio with Professor Pippard's formulæ when the load factors are taken as 7 and 4 respectively. Furthermore, the statistics show that the total weights for present-day commercial aeroplanes may be supposed, in general, divided into three equal parts, (1) structure weight, (2) power unit weight and (3) commercial load, it being supposed that the power unit includes fuel, tanks, etc., and commercial load embraces heating and lighting equipment and all passenger conveniences.

(B) *Engine Weight.*—From stress considerations alone the weight of the engines per b.h.p. should increase continually with engine h.p., but in practice the reverse seems to occur. In Fig. 6 is plotted the weight of the engine (bare) per b.h.p. on h.p. base for several engines both water-cooled and air-cooled. The average curve through the points shows a very rapid increase in the weight ratio below 400 h.p. and above this power the ratio becomes almost constant. It might be expected from general considerations that for very small powers the weight ratio would be large and decrease as the power increases until it reaches a minimum, when it would increase again and ultimately follow the theoretical stress law except in as far as thermodynamic effects enter into the

problem. The minimum ratio evidently occurs for present-day engines at a power greater than 500 or 600 b.h.p.

A large part of the engine weight is usually referred to as engine accessories. Under this heading are included parts such as pipes and tanks, which depend for their weight upon the particular machine in which they are installed and the proposed duration of flight. For such reasons a discrimination is made between the engine weight bare and the weight of accessories. The latter weights have been plotted in Fig. 7 for water- and air-cooled engines and as can be seen from the two points representing the 200 Hispano Suiza the weight of the accessories

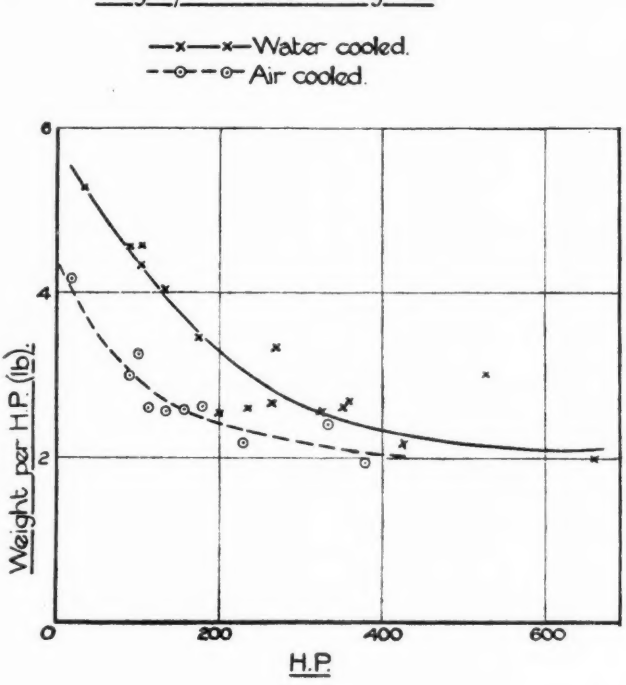


FIG. 6.
Structural Weight of Component Parts.

is considerably affected by the way the engine is installed in the machine. In general, the weight ratio may be taken as 1lb. per b.h.p. for water-cooled and 0.5lb. for air-cooled engines. There appears to be a marked tendency, however, in air-cooled engines for the ratio to decrease with power. The difference between the ratio for air- and water-cooled engines, is, in the main, due to the water carried by the latter.

For further information on the variation of weight with engine size, the fuel and oil consumptions have been plotted in Figs. 8 and 9 respectively. The curves obtained indicate a slight advantage for the larger engine. As regards fuel consumption, much depends upon the position of the air intake, compression ratio, etc., but the curve of Fig. 8 gives a rough indication of the general effect of engine size on this quantity.

THE STRUCTURAL WEIGHT OF COMPONENT PARTS

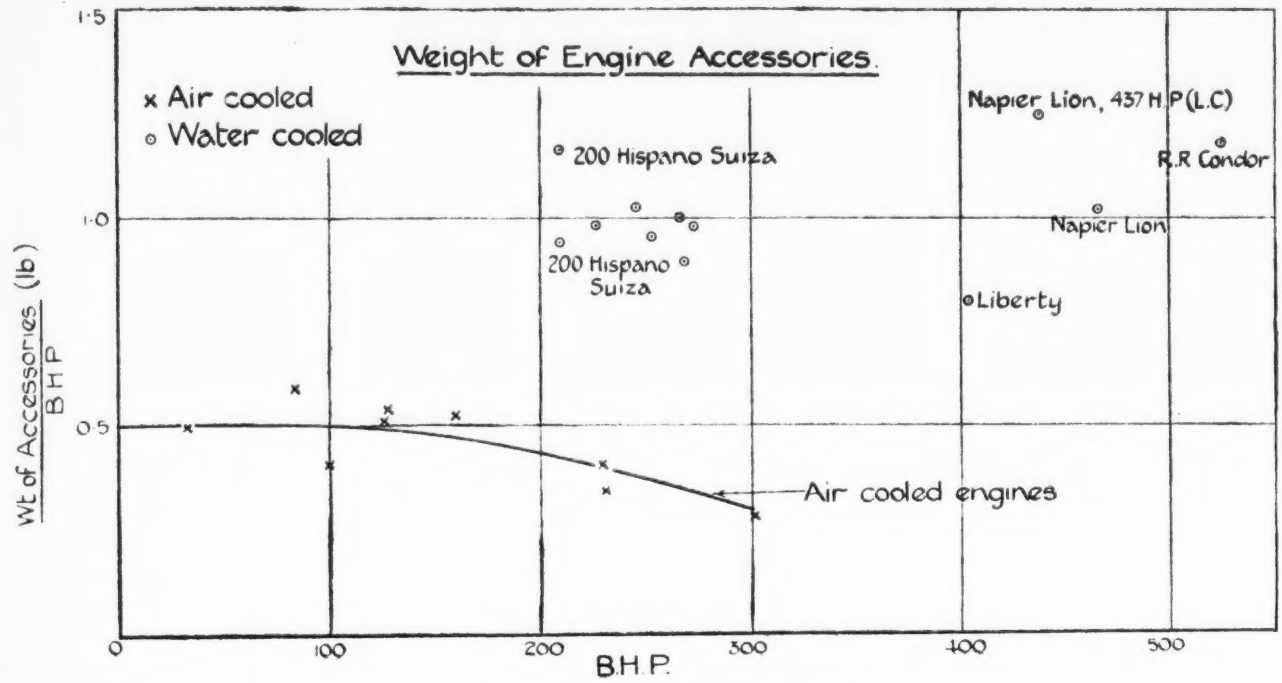


FIG. 7.

FUEL CONSUMPTION.

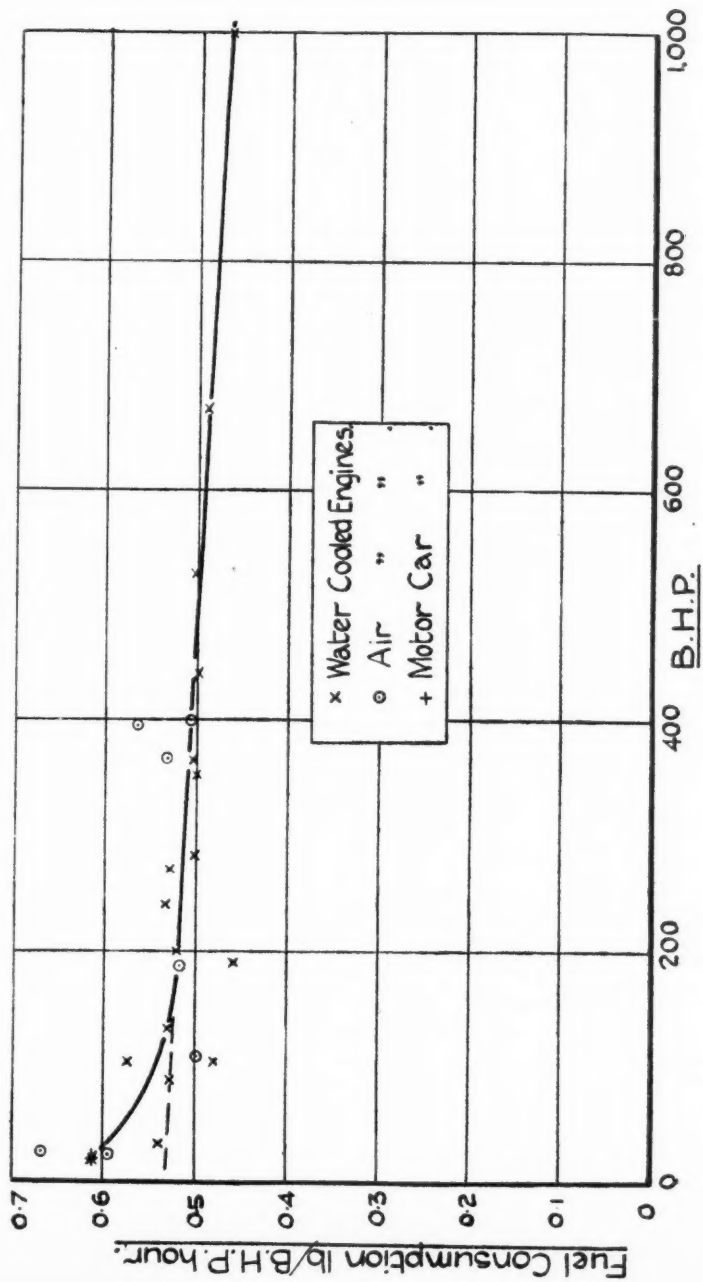

FUEL CONSUMPTION.
Per normal B.H.P. for normal running.
Fuel Consumption lb/B.H.P. hour.
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
0
200
400
600
800
1,000
B.H.P.
× Water Cooled Engines.
⊙ Air " "
+ Motor Car "

Fig. 8.

Fig. 7.

Reverting to Figs. 6 and 7 it will be seen that the air-cooled engine installation is considerably lighter than the water-cooled for powers below 400 b.h.p. and at high powers tends towards a difference of 0.5lb. per b.h.p., that is, the amount equal to the difference in weight of the accessories. From this it would appear more economical to use air-cooled than water-cooled engines in air transport work, especially as the reliability of the former is reputed to be greater than that of the latter and the repair bill smaller, unless the facts that water-cooled engines are at present made of higher power and that better stream-lined bodies can be constructed with these engines, become deciding factors.

In connection with the latter it is interesting to compare the relative aerodynamic merits of machines using water- and air-cooled engines.

An opinion is held by many designers and aerodynamic experts that the aerodynamic resistance due to the cylinders of an air-cooled engine is very large and that its effect outweighs the advantages that engine might have over the water-cooled engine. Unfortunately, data on the subject is very slight and it is only by indirect argument that any opinion can be expressed.

An early attempt at studying this question was made at the N.P.L.* where the resistance of a model of the body of the "Weasel" aeroplane was measured in a wind tunnel and again measured when the shapes representing the cylinders of the air-cooled engine were removed. From these tests it was estimated that the full scale body resistance was 61.6lb. at 100 ft./sec. and that the removal of cylinders reduced this figure to 24.4lb.

To compare this effect with the performance of a machine having a water-cooled engine, it might be supposed that (*a*)† the body resistance is in general about 40 to 50 per cent. of the resistance of the whole machine, (*b*)‡ the increased resistance due to placing a honeycomb radiator 2.5 sq. ft. area in the nose of the body of a 200 h.p. machine is approximately equal to the resistance of 1.5 sq. ft. of radiator in the stream behind the airscrew, and (*c*)§ the resistance of the latter is $0.00075\ V^2$ lb. per sq. ft., where V is the speed of the stream in ft./sec. (95 m.p.h. + 30 per cent. for slip-stream effect). From these figures it follows that the drag of a machine with an air-cooled engine is 130 per cent. that of a machine with a water-cooled engine and a nose radiator.

Now the saving in engine weight on an aeroplane of the size of D.H.34, if an air-cooled engine were used instead of the water-cooled engine, would be of the order of 250lb., but this saving is far outweighed by the increased resistance of 30 per cent. In fact the 250lb. decrease in weight is equivalent to about 5 per cent. decrease in resistance, and it can only be concluded from these figures that the substitution of an air-cooled for a water-cooled engine would produce an effect equivalent to an increase of 25 per cent. in the resistance of the machine. This effect is very large and would mean that, in machines of the type of D.H.34, the rate of climb would be halved if the total weight were made the same in the two cases; or that about 2/3rds of the commercial load would have to be sacrificed if the same climbing speed were to be maintained.

If this effect were true generally, one would expect to find a considerable falling off in performance of the air-cooled machine compared with those using water-cooled engines. To investigate this point an analysis has been made of the performances of a number of machines which have been tested under ordinary

* R. & M. 465. "Tests of a Model of the 'Weasel' Aeroplane Body." By H. B. Irving, B.Sc.

† R. & M. 659. "Full-Scale Determination of the Lift and Drag Coefficients of Biplanes by Means of Engine and Airscrew Performance." By the Aerodynamics Staff of the R.A.E.

‡ R. & M. 738. "A Comparison of the Rates of Heat Dissipation of an Understrung and Nose Radiator on S.E.5. (S.E.5A and S.E.5B.)" By the Aerodynamics Staff of the R.A.E.

§ R. & M. 221. "Experiments on the Resistance and Cooling of Radiators." By L. W. Bryant and H. B. Irving.

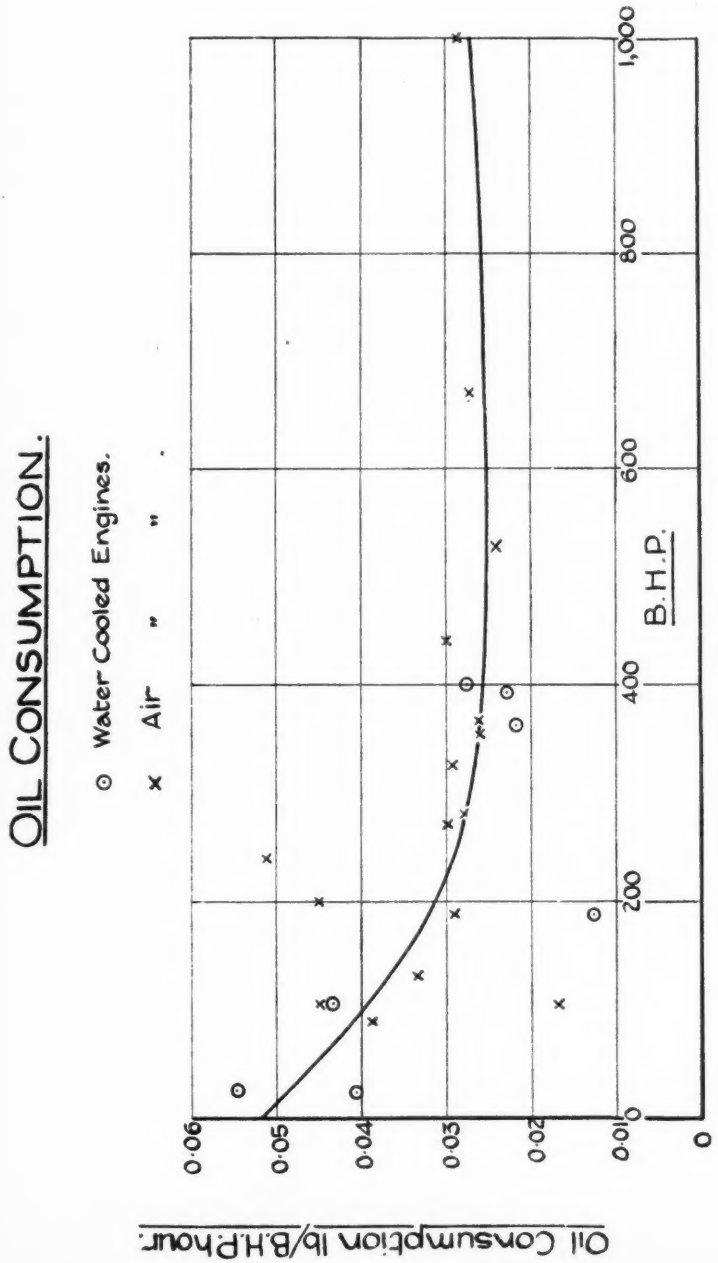

OIL CONSUMPTION.
⊙ Water Cooled Engines.
× Air " "
Oil Consumption lb/B.H.P.hour.
0·06
0·05
0·04
0·03
0·02
0·01
0
0
200
400
600
800
1,000
B.H.P.

FIG. 9.

flight conditions. The names of the engines used in these machines and performance figures, etc., obtained from the full-scale tests are given in Table 4.

TABLE 4.

Engine.	Max. Ground Speed V.	H.P. at Max. Speed.	L/D at Max. Speed.	wt./wing area.	$\frac{V}{\sqrt{\text{wt./wing area.}}}$
	AIR-COOLED ENGINES.				
	m.p.h.			lb./sq. ft.	
Jaguar	138	370	3.92	9.3	45.5
,, ...	149	368	3.96	10.25	46.5
,, ...	143	377	4.37	8.5	49.0
2 Jupiters	125	810	4.75	8.56	42.8
,, ...	124	810	5.18	9.41	40.4
Jaguar	126	349	5.1	9.36	41.3
	WATER-COOLED ENGINES.				
Napier Lion	143	442	4.60	8.49	49.2
Hispano Suiza	134	316	3.94	7.31	49.5
R.R. Falcon Mk. III. ...	113	276	4.98	7.84	40.4
2 R.R. Eagle VIII. ...	107	718	5.60	7.6	38.9
,, ,, ...	104	718	6.88	9.5	33.8

To compare the performances the lift/drag ratio has been calculated for each machine at its maximum flight speed on the assumption that the airscrew efficiency was 70 per cent. These values have been plotted in Fig. 10 on a base of (max. speed)/(square root of the wing loading), a ratio which is proportional to the speed range of the machine assuming the maximum lift coefficients to be the same. The table and chart show that there is no marked difference between the two types of machines.

In Table 5 are given the values for the lift/drag ratio calculated for flight at the ceiling of each machine. It has been assumed in the calculations that all the engines followed the density law of variation of power with height usually employed in analysis and that the airscrew efficiency was again 70 per cent. The table shows that apart from one exceptionally high value of lift/drag for a water-cooled machine, no aerodynamic advantage is possessed by such machines over the air-cooled.

TABLE 5.

Ceiling. ft.	Indicated Speed at Ceiling. m.p.h.	H.P. at Ceiling.	L/D at Ceiling.
22,050	67.5	353	7.3
22,250	66	336	7.2
22,000	63	351	7.55
18,000	56.5	765	6.3
15,500	58.5	765	6.2
19,000	68.5	335	8.6
25,300	69.5	424	10.8
21,000	60	284	6.75
18,300	56	264	7.45
14,650	59.5	685	7.45
7,750	62.5	690	6.5

Although the full-scale data does not reveal any aerodynamical advantage for the water-cooled engines, the data are too scanty to be conclusive. On the other hand, the model test on an old design is only an isolated case, but it serves to

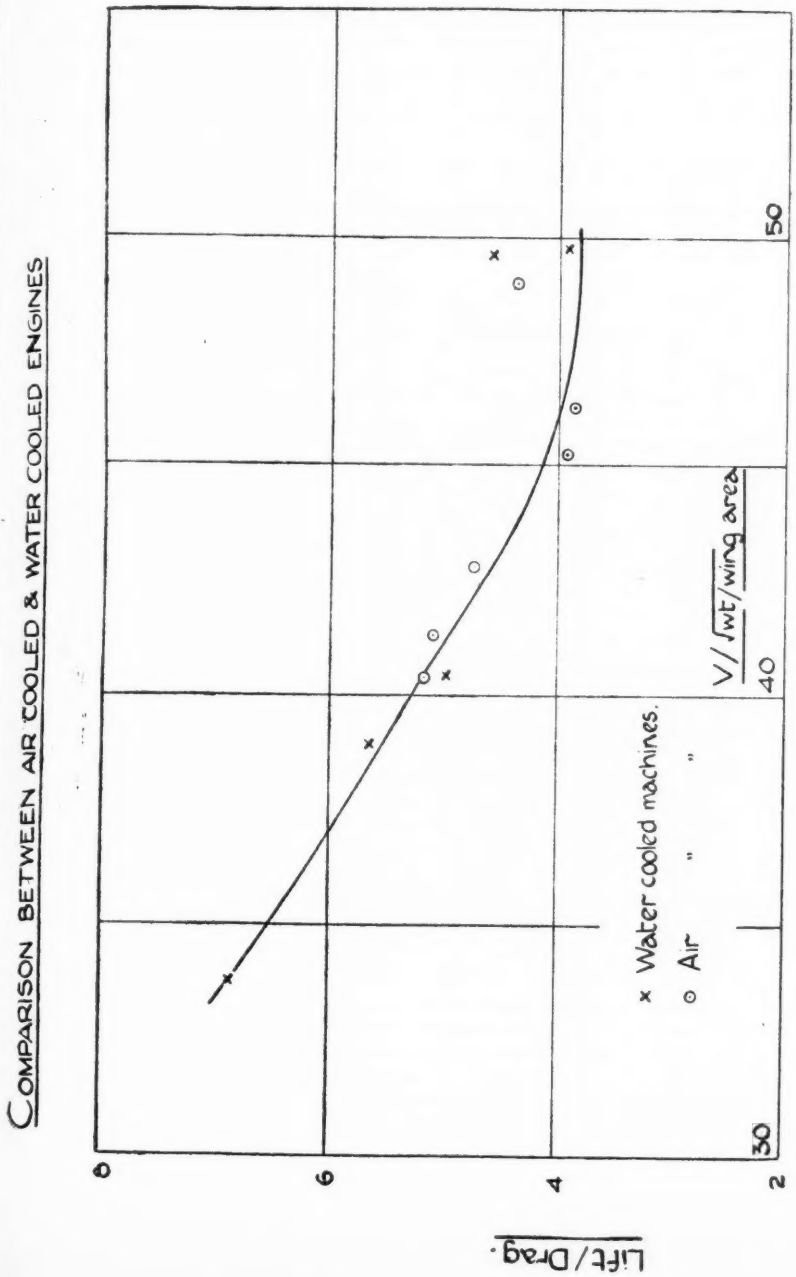

COMPARISON BETWEEN AIR COOLED & WATER COOLED ENGINES
Lift/Drag.
8
6
4
2
30
40
50
V/√wt/wing area
× Water cooled machines.
○ Air " "

FIG. 10.

show to what a large extent the body resistance might be increased by the effect of the cylinders of the air-cooled engine. It is almost impossible to say how the body resistance will be affected by the modifications at the nose produced by the cooling system, and it is quite possible that the clear outline appearance of the nose of a body fitted with a honeycomb radiator gives a false impression. In view of the large effect found by the model test, there appears to be ample scope for research in this matter, and it may be possible to improve the machine considerably by fine stream-lining of the nose and cooling the water by means of wing or of underslung radiators. The effect of underslung radiators found on the S.E.5 might not represent the full advantage that can be obtained in this respect as it is not evident that the modified body used was stream-lined to anything approaching the best advantage.

As far as statistics on full-scale work are concerned, however, it would appear advantageous to use air-cooled engines on air transport machines and to construct these machines large enough to take the highest powered engines. In this latter respect it must be noted that water-cooled engines are constructed of higher power and for this reason alone these engines might be more economical, but, with the tendency now for using three-engined machines in aircraft transport, the air-cooled engine might be found more suitable.

The analysis of engine statistics, etc., above shows that it is advantageous to use very large engines and that it is preferable the engines should be of the air-cooled type unless the designer can be confident of decreasing the aerodynamic resistance by using water-cooled engines.

(C) *Body Resistance.*—The model tests on the "Weasel" body indicate that the improved stream-lining brought about by removing the cylinders of the engine decreases the machine resistance to about 3/4ths of its original value. Such an improvement if it could be obtained in practice would result in a considerable economic gain. Very little is known of the aerodynamic properties of aeroplane fuselages, and although it appears very optimistic to expect such a large decrease in body drag as this, even if wing radiators were used, improvement might well result from an extensive aerodynamic investigation into the subject.

With the present state of knowledge it can only be assumed for the purposes of determining the optimum size for commercial aircraft that the resistance coefficients of all good streamlined bodies (resistance $\div \rho L^2 V^2$) are the same where the linear scale used in evaluating the coefficients is the cube root of the volume of the body. This is not general, but it might well be supposed that, of all shapes suitable for aeroplane bodies, only those having a low coefficient defined in this way would be used on commercial machines, and therefore once an efficient set of shapes has been decided upon, the effect of increasing the size of the machine would be equivalent to increasing the resistance of the body by the law

$$\text{body resistance at cruising varies as } (\text{volume})^{2/3} \quad . \quad . \quad (9)$$

since the cruising speed may be regarded as fixed.

In commercial aircraft the fuselage space is mainly taken up by the passengers' cabin and luggage compartments, and although the engine occupies a fair percentage of the space, it may be supposed that the engine size will increase with the commercial load and that to a sufficient degree of accuracy the volume of the fuselage may be taken as proportional to the latter. Under these conditions the above law becomes

$$\text{power absorbed by body at cruising varies as } (\text{commercial load})^{2/3} \quad . \quad (10)$$

if it also be assumed that the airscrew efficiency is not altered and that the effect of the airscrew slipstream remains substantially the same.

Economic Machine Size

To study the economic effect of increasing the size of the machine, it is first necessary to study how the various items of Table 1 become affected. In the

main, the expenses can be approximately divided into four groups, viz., (1) those directly associated with the engine, such as repairs, maintenance, fuel, etc.; (2) the machine; (3) the pilot staff, wages and insurance; and (4) the passenger. The expenses of any one group are almost independent of modification in the others, thus if the line were redesigned so that the construction of the machines, number of passengers and pilots' duties altered, but the engines and the work they perform were allowed to remain unchanged, the expenses incurred by the engines would not alter. Similarly, the extra expense incurred by increasing the pilots' duties will not be affected, in general, by questions such as the number of passengers carried per trip or whether more or less expensive aircraft or engines are used. Table 6 shows approximately how the various expense items of Table 1 are divided between these four groups.

TABLE 6.

DIVISION OF EXPENSES IN POUNDS STERLING.

	Engine.	Machine.	Pilot.	Passenger.
Capital charges	62,500	74,000	—	29,000
Running costs				
(1)	28,519	—	—	—
(2)	10,500	10,500	18,600	—
(3)	6,500	6,500	—	5,000
(4)	14,375	22,600	—	—
(5)	14,475	20,850	1,440	—
(6)	3,500	3,500	—	—
(7)	—	—	—	10,000
Interest	3,750	4,440	—	1,740
Percentage of total	43.6	36.5	10.9	9.0

For applying this table it might be assumed that these figures are derived from an air line using machines having all up weights of 7,000lb. and engine power of 450 h.p. Further, it might be assumed that the engine and costs for any other machine are proportional to the horse-power P; the machine costs to the weight w_s; the passenger costs to the commercial load w and the pilots' salaries to the time of flight which is fixed for each machine as $3\frac{1}{2}$ hours. Thus, the ratio of the expense per machine used on the air line having the modified design of machine to that for the standard machine is given by

$$E = 0.00007\,P + 0.000157\,w_s + 0.109 + 0.0000386\,w \quad . \quad . \quad (11)$$

where the weights are taken in lbs.

The quantities P, w_s and w can be connected if it be assumed that (*a*) the engine and fuel weight w_e is proportional to the power P as is approximately the case for large powers (see Figs. 6 and 8); (*b*) the drag horse-power of the wings is proportional to the total weight; (*c*) the drag horse-power of the body varies as $w^{2/3}$; (*d*) for the standard machine half the power is absorbed by the wings and half by the body; and (*e*) that the total weight is divided into three equal parts in the standard machine, viz., structure, power unit weight and commercial load. The assumptions (*b*) and (*c*) give the relation if the airscrew efficiency remains unchanged.

$$(w_s + w_e + w)/7000 + (w/2333)^{2/3} = P/225 \quad . \quad . \quad . \quad (12)$$

where w_e is the weight of engine and fuel in lbs.

It is now proposed to find the size of the machine that will produce the lowest cost per ton mile of commercial load first assuming that the structure weight ratio remains constant as appears to be the case over the full range of present-

day machine sizes, and secondly, assuming the theoretical law that the structure weight varies according to the 1.5th power of the total all-up weight.

Economic Machine Size—Constant Structure Weight Ratio

In the first case the expense ratio becomes

$$E = 0.109 + 0.000205\, w + 0.00230\, w^{2/3} \quad . \quad . \quad . \quad (13)$$

The income of the machine will be proportional to w the commercial load, so that the expense ratio per lb. of commercial load will be

$$2333\, E/w = 254/w + 0.478 + 5.5/w^{1/3} \quad . \quad . \quad . \quad (14)$$

From this formula it can be seen that the expense ratio decreases continuously with increase of machine size and therefore it is most economical to build machines as large as possible until the law of constant structure weight ratio breaks down and the effect of this weight predominates. It appears that this position has not yet been reached in present-day practice. In Fig. 11 the expense ratio is plotted for machines up to about 26,000lb. all-up weight, together with the weight per horse power ratio and the ratio between the commercial load and the total weight. The improvement produced by a machine of about 26,000lb. total weight amounts to a reduction of about 25 per cent. in the passengers' fares. For extremely large machines the maximum reduction would be about 50 per cent. The curves for weight per horse power ratio and the ratio of commercial load to total weight (see Fig. 11) show that both these ratios continually increase with increase in machine size, the former increasing by about 17 per cent. and the latter by about 14 per cent. for a machine of 26,000lb. compared to the standard case of the 7,000lb. machine.

For these calculations it has been assumed that the ratio between the structure weight and the total all-up weight remains constant. The fact that it does remain nearly constant in practice is probably due largely to the lowering of the load factor with increase in size of machines. With small machines it is desirable to have a large load factor owing to the greater ease in general with which such machines can be manœuvred compared with large machines. For commercial work, however, highly manœuvrable machines are not essential and it is very probable that the load factor used upon present machines cannot be reduced much further for the design of larger machines. An investigation similar to the above, therefore, but assuming that the factor of safety remains constant, so that the theoretical stress law holds for structure weight in machines larger than the standard here adopted, will give a lower limit to the optimum size of the machine and a mean between the two cases would give a rough indication of the probable law of variation of economy with machine size.

Economic Machine Size—Theoretical Stress Law

The law given by Professor Pippard for the weight ratio of the structure of bombing machines shows that with a factor of safety of 4, about 60 per cent. of this weight is directly designed from stress considerations. This portion it will be assumed varies according to the 1.5th power of the load in the members. In general, this load varies as the lift on the machine less the structural weight of the wings, but there is very little error in assuming that it is proportional to the total weight of the machine. For the purposes of the present calculation the structure weight has been taken as

$$w_s = 0.137\, W + 0.00235\, W^{3/2} \quad . \quad . \quad . \quad . \quad . \quad (15)$$

where W is the total weight of the machine in lbs.

Other formulæ deduced are:—

$$\text{Horse-power } P = 0.0321\, W + 1.28\, w^{2/3} \quad . \quad . \quad . \quad (16)$$

$$\text{Engine unit weight } w_e = 0.160\, W + 6.65\, w^{2/3} \quad . \quad . \quad (17)$$

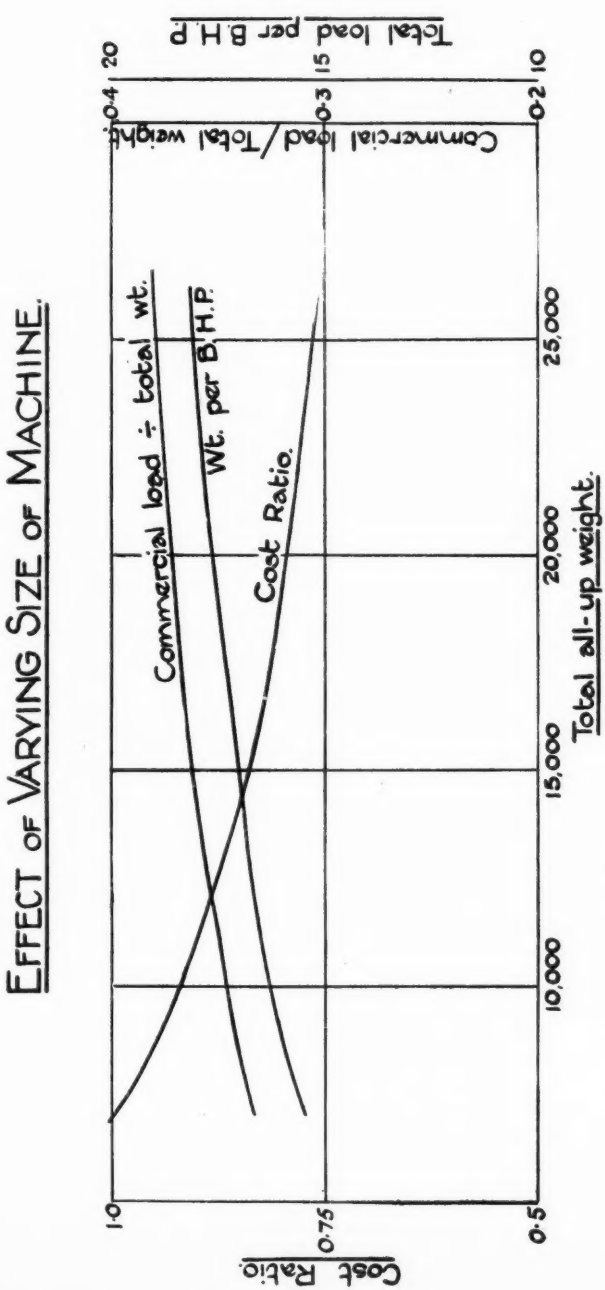

EFFECT OF VARYING SIZE OF MACHINE.
Commercial load / Total weight
Total load per B.H.P
0·4
0·3
0·2
20
15
10
Commercial load ÷ total wt.
Wt. per B.H.P.
Cost Ratio.
Cost Ratio
1·0
0·75
0·5
10,000
15,000
20,000
25,000
Total all-up weight.

FIG. 11.

From these, using (12) above, formula (18) is obtained,

$$0.697\ W - 0.00235\ W^{3/2} = w + 6.65\ w^{2/3} \quad . \quad . \quad . \quad (18)$$

The expense ratio, *i.e.*, the ratio of the cost per ton mile for total weight W to the standard case, is

$$2333\ E/w = (255 + 0.427\ W - 0.016\ W^{3/2} - 0.345\ w)/w \quad . \quad . \quad . \quad (19)$$

where w is the commercial load in lbs. and E has the meaning adopted in (13).

From these formulæ the expense ratio was calculated and found to remain practically constant over a range in total weight from 7,000 to 10,000lb. The results obtained are given in Table 7 (second assumption). In the same table are given for comparison the results obtained, assuming constant structure weight (first assumption) together with the means for the two methods.

TABLE 7.

Machine Weight. W (lb.).	Expense Ratio. 1st Assumption.	2nd Assumption.	Mean.
7,000	1.00	1.00	1.00
8,000	0.96	0.99	0.97
9,000	0.93	0.98	0.95
10,000	0.91	1.01	0.96
15,000	0.83	1.12	0.97
20,000	0.79	1.25	1.02
25,000	0.76	1.41	1.08
30,000	0.74	1.61	1.17

Very little variation in the mean expense ratio occurs between $W = 7{,}000$ and $W = 25{,}000$lb., but the great difference between the results based on the two assumptions shows the necessity for research into the question of structure weight. If the practical law of structure weight variation, viz., structure weight a constant percentage of the total weight, is not due entirely to the fall in the load factor, but still holds for very large machines, then a very large improvement should result from increasing the machine size.

There is a marked tendency at the present day towards increasing the machine size for transport work, and three-engined machines are coming into operation. When the number of engines is multiplied in aircraft, the probability of engine failure might be greatly increased and the reliability of the service suffer, but if, as in the case of a three-engined commercial machine, flight can still be maintained with one engine out of action, the resulting effect upon reliability might be a substantial gain. It would prove instructive to make a short study of reliability and estimate its economic cost.

Reliability

It can be assumed that the policy of an air line is to evolve a reliable and convenient service for its customers so that air transport will advance to give a steady return to as large an amount of capital as possible. For this it is imperative that the service be made safe and reliable; modifications in fact that work to this end will ultimately prove of economical value although their direct effect might appear to be uneconomical.

Reliability is primarily the outcome of general improvement in design resulting from experience and research. If any particular part proves troublesome, this part must be studied and its design improved or replaced by a more reliable mechanism if that is possible. The reliability of the function of an unreliable part can be greatly increased, however, by multiplying the number of the troublesome units in such a way that should one unit fail the others could continue to carry out the work without any alteration in the performance or in some modified form.

By way of illustration consider the common engine practice of doubling the number of plugs in the engine. If only one plug were fitted to each cylinder it would be found that on an average a certain percentage of the runs would be spoilt through plugs misfiring or through the magneto or electrical circuits developing faults. But, however, two magnetos and two sets of plugs are fitted forming two independent systems so that if one were to go out of action the other would perform the full work. Failure in this case would only occur if both systems became defective together and the probability of this would be equal

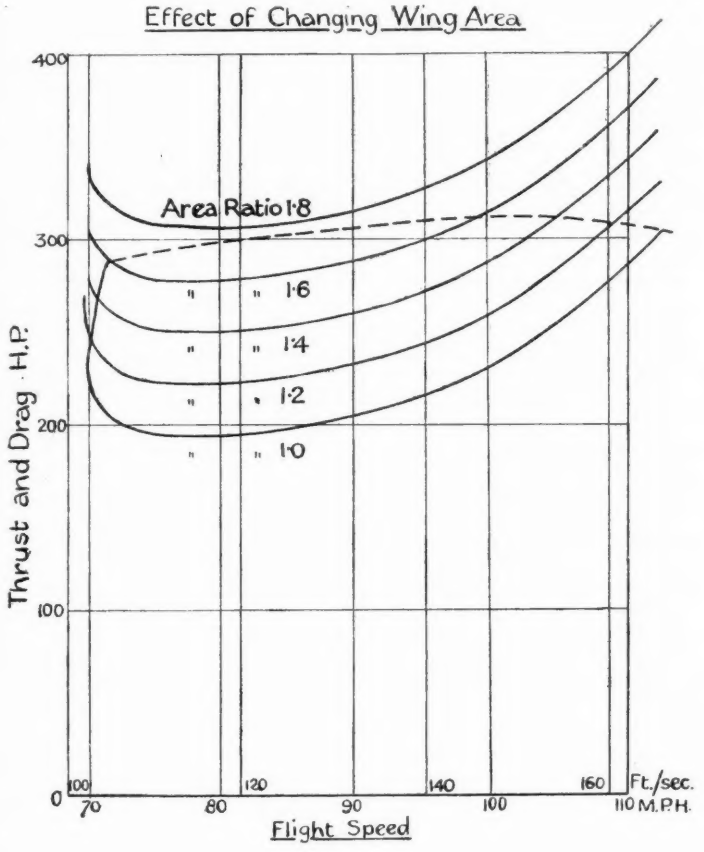


FIG. 12.

to the square of the probability ratio for the failure of one system. If three systems were fitted the probability of failure would drop to the cube of the original probability ratio and so on. The probability of failure is the ratio between the number of times the unit will fail to the total number of times the unit is used, this latter number being supposed very large.

These ratios show that a very great increase in reliability results from the multiplication of the unit. Thus, although considerable improvement in design would be required to increase the reliability of one system from having 1 failure in 10 to 1 in 100 on the average, this improvement would result without altering

the design of the unit if two systems were used, and further, by using tw systems of the improved design, viz., that which has only 1 failure in 100, th trouble would practically disappear altogether, as under these circumstance only 1 failure would occur in 10,000 operations.

Other unreliable units such as oil pressure relief valves could be multiplie in this way to increase reliability, precautions being taken, of course, that is possible to run efficiently on only one in the event of the other failing.

Engine Reliability and the Multi-Engined Machine

The same principle applies to a modified extent when the engine units ar multiplied as in the multiple-engined machine. Primarily the multi-engine machine is designed for the purpose of obtaining a large machine, but increase reliability is considered one of its advantages. It is now proposed to study hov the reliability varies with the multiplication of the engines.

The reliability factor of an engine or an aeroplane might be defined as follows. Suppose a very large number of single-engined machines are set running under normal working conditions. From time to time machines will stop throug various mechanical troubles. These troubles will be supposed purely accidental. Thus, it will be regarded that through accident a machine was fitted with a defective part or that dirt or water stopped the petrol supply to the carburetto jets. If the number of machines running at time t be divided by the numbe running at the beginning of the test, the ratio might be termed the reliabilit factor for this instant, and if the ratio be plotted on a time base the reliabilit curve of the machine will be obtained. Assuming that all accidents are equall probable and neglecting the effect of ordinary wear, the probability curve wil start from unity at $t=0$ and follow approximately the law $y=e^{-at}$ where y is the ratio between the number running to the total number of machines and a is a constant, since the ratio between the number running after a given interval o time to those running at the commencement depends only upon the time interval. This curve, obtained from a collection of machines, may be applied to each machine separately, the ordinate being a measure of the probability that the machine wil be found running after a time t and is therefore a measure of the reliability of the machine. When this law is applied to engines a will depend upon both the h.p. developed and the engine speed.

The effect of multiplying the engines differs considerably from that o duplicating the ignition system as discussed above. Thus if one plug only fires in the cylinder, the engine power is developed just the same as if both were working but when engines go out of action in multi-engined aircraft the conditions change completely. To maintain normal flight the lost power of these engines must be made up by increasing the output of those still in working order and moreover the degree to which this can be carried is limited by the maximum power these engines will produce.

In the case of the D.H.34, a machine largely used by the British air lines during the past few years, the minimum drag horse-power is about 200 and the maximum thrust horse-power available at the same speed is about 300. It might be supposed that this ratio holds generally in air transport work and therefore it might be regarded that not more than 1/3rd of the engines of a multi-engined aeroplane must fail if level flight is still to be maintained.

The reliability factor of a multi-engined aeroplane can now be compared with that of a single-engined machine using an engine of the same type, if it be assumed that the reliability of the engine is the same under all conditions of working. The effect of removing this assumption will be studied later.

Let n be the number of engines in the aircraft and r_0 the least number of engine failures permissible, viz., the largest number less than $n/3$, then the probability that all engines stop during the journey is $(1-R)^n$; for all but one

${}^nC_1R(1-R)^{n-1}$ and for all but p engines it will be ${}^nC_pR^p(1-R)^{n-p}$. Now all these cases will operate to prevent flight if p is less than $n-r_0$. The probability that the machine will not fly, therefore, is

$$F=\sum_{p=6}^{p=(n-r_0-1)} {}^nC_pR^p(1-R)^{n-p} \quad . \quad . \quad . \quad . \quad (20)$$

Most of the terms of this series are very small and can be neglected. Thus, by dividing the term for $p=p$ by the term for $p=p-1$ we get

$$\{(n-p+1)/p\} \times R/(1-R) \quad . \quad . \quad . \quad . \quad (21)$$

The ratio R would be very small to fall below 0.8 and might be taken as greater than 0.9. Again, as an extreme value, one might take r_0 as $n/4$ and therefore the highest term in (20) will be at least twelve times greater than the next highest and the remaining terms will decrease even more rapidly. Under these circumstances the probability that the machine will not fly may be written as

$$F=\{n!/(n-r_0-1)!(r_0+1)!\}R^{n-r_0-1}(1-R)^{r_0+1} \quad . \quad . \quad (22)$$

From this formula charts could easily be drawn giving engine reliability for groups of n engines for various values of the reliability factor R and of the ratio r_0/n. For commercial work r_0/n may be taken as 1/3 and R for normal running as 0.975. The latter figure is based on statistics of forced landings on certain aircraft, a summary for which is given in Table 8. Table 8 applies to a flight of about three hours' duration.

TABLE 8.

FORCED LANDINGS FOR CERTAIN BRITISH MACHINES.

Cause.	No. of Forced Landings.	Percentage.
Weather	213 } 236	= 6.7 per cent. of total flights and 66.8 per cent. forced landings.
Darkness	23 }	
Engine or Installation Failure ...	87	= 2.5 per cent. of total and 24.7 per cent. of failures.
Other reasons	30	= 0.8 per cent. of total and 8.5 per cent. failures.
Total forced landings	353	= 10 per cent. of total flights.
Total flights commenced (one year)	3,502	

As an example, the cases have been worked out in Table 9 of one to nine-engined machines, having the same type of engines and a reserve power of one-third of the maximum.

TABLE 9.

No. of Engines.	1	2	3	4	5	6	7	8	9
Percentage reliability factor of group	97.5	95.0	99.87	99.74	98.74	99.97	99.95	99.92	99.995

This table shows that the two-engined machine is much less reliable than the single-engined machine and the five-engined machine but little better than the latter. With the three-engined machine the failures drop from 25 to one per thousand and for more than six engines per machine the reliability is very high.

In this table it has been assumed that the reliability factor is constant for all conditions. Thus, the figures 97.5 and 99.87 per cent. give the percentage of reliable flights for two services, one using single-engined machines and the other using a third of the total number of machines used in the first service, but each having three engines per machine. All the engines are of the same type. If the engine types are different in the two cases the appropriate values for R must

be used to make strict comparison. The assumption also implies that the reliability factor is the same both when the engines are used at higher power, such as when one engine fails in a three-engined machine and the power of the other engines is increased to maintain flight, and when the engines are working under normal conditions. This assumption might be far from the truth and the reliability factor of 0.975 for one engine might drop for some engines to 0.9. The effect of this alteration in reliability entails a rather complicated modification of the above formula for the factor of failure, but it can be easily illustrated if attention is confined to a comparison between the three-engined and the single-engined machines.

Let a_1 be the reliability index for normal working in the reliability factor formula $R=e^{-at}$ and a_2 the index for the engine working full out. Suppose that a very large number of machines are sent off on the journey. Let N_0, N_1, N_2 and N_3 be the number of machines at a particular time t which have 0, 1, 2 and 3 engines working. Now if N be the number of machines at the start of the journey it can easily be shown that

$$N_3=Ne^{-3a_1t}=NR_1^3 \quad . \quad . \quad . \quad . \quad (23)$$

Between time t and $t+\delta t$, the number of machines having three engines working will decrease by $3a_1N_3\delta t$, so that of N_3 machines running at time t, at time $t+\delta t$,

$N_3e^{-3a_1\delta t}$ will have three engines running.
$N_3 \cdot 3e^{-2a_1\delta t}(1-e^{-a_1\delta t})$ will have two engines running.
$N_3 \cdot 3e^{-a_1\delta t}(1-e^{-a_1\delta t})^2$ will have one engine running.
$N_3(1-e^{-a_1\delta t})^3$ no engines running.

Of N_2 machines having two engines running at time t, $2a_2N_2\delta t$ machines will fail owing to more engines going out of action, the reliability index of this group being a_2. Thus,

$$dN_2/\delta t+2a_2N_2=3a_1N_3$$

giving

$$N_2=\{3a_1N/(3a_1-2_2a)\}(e^{-2a_2t}-e^{-3a_1t}) \quad . \quad . \quad . \quad (24)$$

and therefore the reliability ratio becomes

$$R=\{1/(3a_1-2a_2)\}(3a_1e^{-2a_2t}-2a_2e^{-3a_1t}) \quad . \quad . \quad . \quad (25)$$

Expanding the exponential terms as far as t^2 and neglecting higher powers we get

$$R=1-3a_1a_2t^2 \quad . \quad . \quad . \quad . \quad . \quad (26)$$

To all practical purposes a_1t may be taken as $(1-R_1)=0.025$ and a_2t as $(1-R_2)=0.1$ for a three hours' flight so that the reliability factor becomes

$$R=1-3\times0.1\times0.025=0.9925$$

thus instead of the failures being reduced in the ratio of about 1 in 20 they are reduced in the ratio of about 3 in 10.

This calculation shows that an increase in reliability still results even if the reliability factor of the engine under full load sinks to 90 per cent., and from formula (26) it will be seen that this factor must reduce to 67 per cent. before the reliability of a three-engined machine drops to that of a single-engined machine, a condition that is highly improbable. The formula also shows, however, that the three-engined machine would have no reliability advantage if the journey were extended to a duration exceeding nine hours, supposing R_2 for the three hours' flight is as low as 0.9, or in general exceeding the time at which a_2t becomes greater than 1/3. To all practical purposes the latter might be taken as equivalent to the condition where the reliability factor sinks to less than 67 per cent., that is, to about three failures in ten flights with the engines running all out over the full course.

The drop in reliability of the machine due to drop in reliability of the engine with increased power will be less as the number of engines per machine is increased.

The Economic Cost of Reliability

The normal running conditions usually employed in practice to meet reliability requirements impose a limitation on the power available from the engine unit, and it is important from an economic standpoint that these running conditions and the economic effects of the limitations should be clearly understood. From the viewpoint of the engine designer, an engine can develop a certain " maximum " power, say, 500 b.h.p., with the throttle full open at a certain " maximum " speed, say, 2200 r.p.m. It is considered inadvisable to exceed these maximum conditions except under exceptional circumstances, and even then only by a very small amount and for a very short time, because undue stresses or vibration might result and cause considerable damage to the engine.

These maximum conditions are considered to be safe running conditions for periods of short duration, but military experience has shown that, for normal running, the speed should be reduced by about 10 per cent., say, to 2000 r.p.m., giving a corresponding power of 450 b.h.p., and these figures are usually taken as the engine rating. In aircraft transport work the speed is still further reduced to 1850 r.p.m. for normal running mainly on account of engine reliability and costs of repairs and overhauls to engine. The maximum power possible at this speed is 415 b.h.p., but for commercial flight the engine is usually throttled down until it develops about 3/4ths of this power, viz., 310 b.h.p. approximately or 62 per cent. of the maximum b.h.p.

It is not clearly understood whether the reduced speed or the reduced power is mainly responsible for the improvement in reliability. Greater economic efficiency would undoubtedly result if more power could be developed and usefully employed at cruising. It is considered by many designers, however, that an increased power at the same engine speed would result in a decreased reliability, but they are non-committal on the question of whether a gain in reliability could be produced by altering the cruising speed of the engine and so counteract the effect of the loss in reliability due to increased power output. From an economic point of view it is desirable to develop as high a b.h.p. as possible at cruising and it is important to know where the limit is imposed by the requirements of reliability.

Where a practical rule has been laid down through experience it sometimes happens that other factors, whose effects are not considered, contribute considerably towards its determination. Thus in design certain conditions not directly affecting the engine might limit, say, the wing loading of machines, and this fact, coupled with prevalent ideas on airscrew design together with the limitations imposed by the engine speed and gear ratio, might result in the cruising h.p. of the engine falling as low as 310 b.h.p. Having arrived at this figure through prevailing practice and also having established an organisation for repairs, etc., accordingly, the operators of an air line would take up rather a conservative attitude towards any suggestion of altering these running conditions.

Although it is not suggested that these should be altered, yet, in order to obtain a general idea of the economic effect of the restriction, a study will be made of the effects that would result if the engine limits were extended and the machine designed to take full advantage of the modification. This question will be answered if it be supposed that the wing area of the machine is varied and other design features altered to correspond.

By altering the wing area the performances of the machine will naturally alter, but the machine specification will fix certain main characteristics. This

specification will be built up on the requirements demanded by the service, and these in turn are dictated to a great extent by the geographical and meteorological features of the country through which the route must pass. Thus in mountainous countries and in regions where temperature changes are great or down-currents prevalent, the ceiling of the machine on the one hand, or the maximium rate of climb on the other, should not be less than certain specified figures. In countries where landing grounds are bad or of small area, the conditions might demand a low landing speed, whereas flight over flat country with good aerodromes at each end might allow of a high cruising speed with a sacrifice of low landing speed. For the purposes of the present calculation it will be assumed that the maximum rate of climb is limited to a minimum of 500 ft./min.

From performance tests on the standard machine of Table 1, the thrust h.p. available and the drag h.p. can be estimated. Typical curves are given in Fig. 12, where the former is plotted as a dotted line and the latter is represented by the full curve. Alteration in wing area and weight of the machine will modify the latter curve only, unless of course the airscrew be redesigned in order to function more effectively under the new conditions. It will be supposed in the first place that the body of the machine remains unchanged and that the wings are increased in area but not altered as far as section, aspect ratio and gap/chord ratio are concerned.

Let the increase in wing area be A, then using the usual symbols for drag coefficient, etc., the increase in drag h.p. will be

$$\rho A V^3 k_d / 550 = \{ (\rho k_{1\,max}) / 550 \} (AVD/L) \quad . \quad . \quad . \quad (27)$$

if the weight of the machine be adjusted so that the minimum speed of flight remains unaltered. L/D is the value of the L/D ratio for the wings and wing struts together. This ratio is given in Table 10, which has been calculated from published data on the R.A.F.15 section. The resistance of the struts and wires has been estimated from some tests carried out at the R.A.E. and has been taken as equivalent to increasing the drag coefficient by 0.0019.

TABLE 10.

V ft./sec. ...	180	158	141	128	109	106
L/D	15.0	15.7	14.7	13.4	10.6	7.1

From the above formula the drag h.p. curves have been drawn in Fig. 12 for the machine when the increase in wing area for each curve is $A = 20$, 40, 60, 80 and 100 per cent. of original area respectively (536 sq. ft.). The weights of these machines are supposed to be such that the landing speed remains the same, that is, the wing loading is kept constant. The weight, however, must be adjusted so that the maximum rate of climb and not the wing loading remains constant.

Now it is noticeable from Fig. 12 that although the maximum h.p. of the engine is nearly 500 b.h.p., only about 300 thrust h.p. is developed at maximum rate of climb. This is due to the efficiency of the airscrew decreasing at low flight speeds and to the fact that the airscrew causes the engine speed to drop, thereby preventing the full development of power. It might be assumed, however, that it is possible to develop 300 thrust h.p. at climb on all the machine modifications now being discussed by designing an appropriate airscrew without altering the efficiency at cruising.

Let W_1 be the new machine weight.

W_0 be the machine weight for the curves in Fig. 12,

then the effect of changing the weight can be found by altering the abscissæ and ordinates of Fig. 12 according to the laws

$$V/V_0 = (W_1/W_0)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad (28)$$

and

$$H/H_0 = (W_1/W_0)^{3/2} \quad . \quad . \quad . \quad . \quad . \quad (29)$$

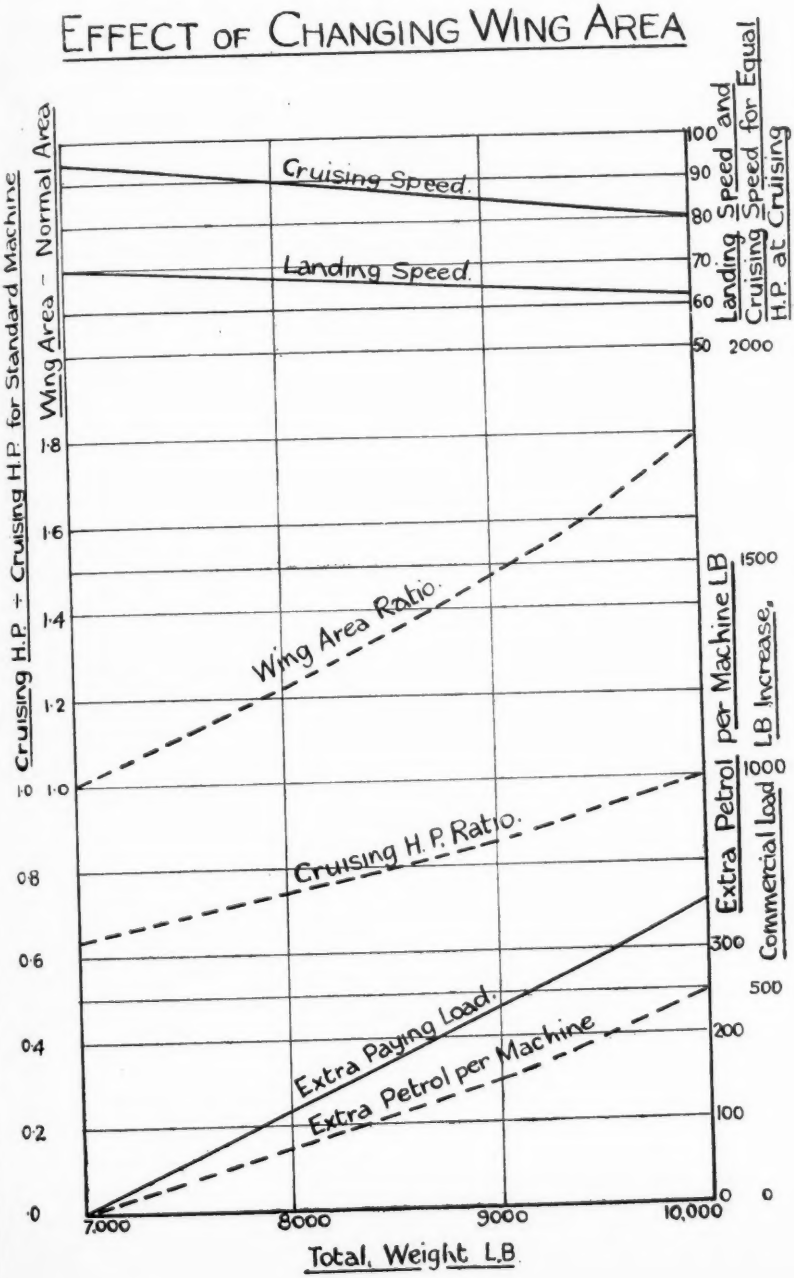

EFFECT OF CHANGING WING AREA
Cruising Speed.
Landing Speed.
Wing Area Ratio.
Cruising H.P. Ratio.
Extra Paying Load.
Extra Petrol per Machine
Cruising H.P. ÷ Cruising H.P. for Standard Machine
Wing Area = Normal Area
Landing Speed and Cruising Speed for Equal H.P. at Cruising
Extra Petrol per Machine LB
Commercial Load LB Increase.
Total Weight LB
7,000
8000
9000
10,000
2000

FIG. 13.

On the assumption that the thrust h.p. at climb is 300, the condition for best rate of climb is obtained when the speed of flight corresponds to minimum drag h.p., under these conditions since the h.p. for climb in the standard machine is 102 h.p. the machine weight can be found from

$$102\ W_1/7000 = 300 - (H_1)_{\min} = 300 - (H_0)_{\min}\ (W_1/W_0)^{3/2} \quad . \quad (30)$$

that is

$$(W_1/W_0)^{3/2} = 300/(H_0)_{\min} - 102\ W_0 W_1/7000\ (H_0)_{\min} W_0 \quad . \quad . \quad (31)$$

In Fig. 13 a curve is plotted showing the variation of the area ratio A_1/A_0 with W_1 the total weight of the machine found from this formula.

The amount of power taken from the engine during cruising can be found from the value of the h.p. for normal wing area at a speed $95\sqrt{W_0/W_1}$ m.p.h., the cruising speed being 95 m.p.h. for all machines. From this value of the h.p. $= H'$ the power at cruising for a modified machine will be

$$H'_1 = (H'_0 W_1/7000)\ (W_1/W_0)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad (32)$$

The ratio between this quantity and $H'_0 = 213$ h.p., the cruising drag h.p. for the standard machine, represents the degree of throttle opening and is plotted as cruising h.p. ratio in Fig. 13. By assuming that the weight of fuel and oil consumed is proportional to the cruising h.p. the fuel consumption weight can be found. The curve for the extra fuel consumed per machine is also given in Fig. 13.

It is possible to determine the speed at which cruising may be carried out in order to give the same throttle condition as at cruising for the standard machine. This can be done by making $H'_1 = 213$ h.p. and calculating H'_0; V'_0 can then be found from the curves in Fig. 12 and V' the cruising speed deduced from

$$V' = V'_0\ (W_1/W_0)^{\frac{1}{2}} \quad . \quad . \quad . \quad . \quad . \quad (33)$$

The results so obtained are plotted together with the landing speed in Fig. 13.

To determine the increase in commercial load account must be taken of the fact that increased cabin space must be supplied to carry the load and this in turn will lead to increased head resistance so that the gain in commercial load will be much smaller than the difference $W_1 - p - 7000$ lb. calculated above, where p is the increased weight of fuel carried. Thus suppose the body increased in volume proportional to the commercial load and let

W = total weight of the machine before modification,
w = gain in weight $= W_1 - p - 7000$ lb.,
W' = original commercial load, say 0.25 W, and
w' = final increase in commercial load,

then for the drag h.p. to remain unaltered the following formula is obtained:—

$$1\ W - w + 1.5\ w'/2W + \tfrac{1}{2}\ \{\ (W' + w)/W'\ \}^{2/3} = 1 \quad . \quad . \quad (34)$$

It is assumed that for the standard machine half the power is absorbed by the body and half by the wings, and that the increase in structure weight (obtained from statistics on aircraft structures) is equal to half the increase in commercial load. This formula leads to

$$w' = 0.24\ w \quad . \quad . \quad . \quad . \quad . \quad (35)$$

that is, the increase in commercial load is only about 1/4th of the increase $W_1 - p - 7000$ lb.

The commercial load calculated in this way is plotted (full line) in Fig. 13.

Effect of Modifications on Cost

The curves showing the increased paying load suggest that a considerable gain in economy would result if the engine output could be increased without adverse effects upon reliability, etc. This apparent gain will now be investigated

on the assumption that no loss in engine reliability or increased engine repairs and maintenance will be incurred. Two cases fall to be considered, (*a*) where the timetable of the line remains constant and the traffic is supposed to increase with the increased machine capacity, and (*b*) where the total yearly traffic remains the same.

In (*a*) the yearly expenses will be increased to all practical purposes by the cost of the increased petrol consumed. This increase, however, is a small percentage of the total expense bill and is more than compensated by the increased carrying capacity of the machine. The cost per ton-mile is plotted in Fig. 14, curve (*a*), for various machine weights.

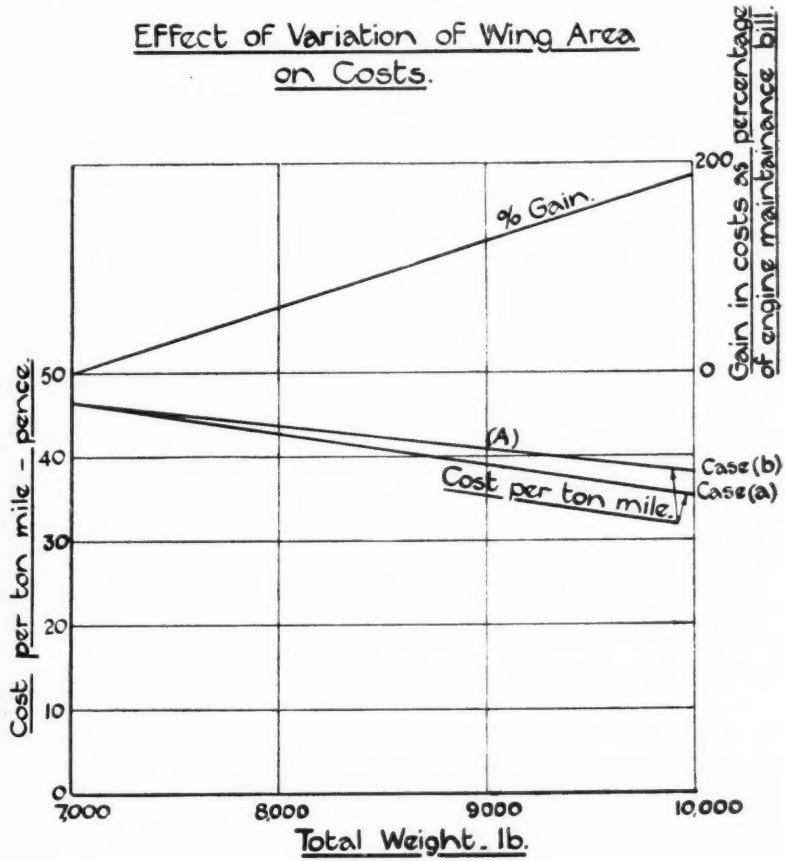


FIG. 14.

For case (*b*) the number of flights per year must be adjusted so that the total traffic carried remains the same. Thus, if r_2 is the number of machine flights per year and r_1 the proportional increase in petrol consumption per machine, the capital and running cost given in Table I will vary approximately according to the table below (Table II).

TABLE 11.

	£
Capital costs	$29{,}000 + 136{,}500r_2$.
Running costs—	
(1) Fuel and Oil	$28{,}519r_1/r_2$.
(2) Staff	$10{,}200 + 29{,}700r_2$.
(3) Renewals	$7{,}000 + 11{,}000r_2$.
(4) Depreciation	$37{,}041r_2$.
(5) Insurance	$36{,}765r_2$.
(6) Landing charges, etc.	7,000.
(7) Sundry	10,000.
Interest at 6 per cent. ...	$0.06\ (2900 + 136{,}500r_2)$.

The curve showing these costs is also given in Fig. 14. To a sufficient degree of accuracy the curves of Fig. 14, cases (*a*) and (*b*), may be supposed to apply to the case in Fig. 13, where the cruising h.p. is maintained constant.

In estimating these costs it has been assumed that the maintenance of the engines under the augmented load remains unaffected. This will not be the case if extra overhauls have to be made to bring the reliability of the service up to the original standard. The costs for the engines depreciation (4), and renewals, repairs and upkeep given in Table 1 for the standard conditions, may be taken as £14,375 and £4,000 per annum respectively. The ratio between the amount of money available for the increased engine maintenance to this cost is also plotted in Fig. 14 for the two classes of traffic. These curves show that a considerable percentage may be expected in this way without the economic efficiency of the line falling below that of the standard case, and it seems highly improbable that an economic gain would not result from increasing the engine power output at cruising and lowering the flight speed at climb. It should be noted that, in the case where the engine output at cruising is maintained constant, the engine maintenance costs remain unaltered.

It is assumed in the above that it is possible to design the airscrew so that sufficient power is available both at climb and at cruising.

Design of Airscrew

To utilise the engine horse-power efficiently, great care must be taken in designing the airscrew. From an economic point of view the airscrew should be designed to develop as high a thrust power as possible under cruising conditions, and from questions of reliability the customary practice is that the engine power developed under those conditions should be about 60 per cent. of the maximum and the engine speed 85 per cent. of the maximum speed. The problem is further complicated by stress considerations; limitations of size; the fact that as high a thrust should be developed as possible when the machine is taking off from the aerodrome and that the thrust horse-power should again be very high during climb. To a great extent these requirements each demand different types of airscrews, but by judicious design it should be possible to effect compromises so that good working conditions are universally obtained.

In the first place airscrews used on commercial aircraft are not so limited in diameter as those used on military aircraft and are not used under such extreme conditions of speed and stress, so that the stress problem should not call for the special consideration it receives in military craft. It is proposed, therefore, in the present discussion to confine attention almost entirely to the aerodynamical problems.

For the selection of the airscrew, choice will be made from a family tested at the N.P.L., the results for which are given in R. & M. 829.* Attention will

* R. & M. 829. "Experiments With a Family of Airscrews, including the Effect of Tractor and Pusher Bodies." Part I. By A. Fage, C. N. H. Lock, R. G. Howard, and H. Bateman.

be devoted at present to the set with two blades of series No. 3, which was built up from blade sections very suitable from stress considerations and upon which a fairly extensive series of experiments were carried out upon variable pitch airscrews. By cross-plotting the results given in the report and interpolating the characteristics, torque coefficient (Q_c=torque/$\rho D^5 n^2$) and efficiency η, given in Figs. 15 and 16 on a V/nD base for various values of the P/D ratio, were obtained,

ρ being the air density,
D the airscrew diameter,
n the engine speed,
V the relative wind speed, and
P the experimental mean pitch, *i.e.*, the value of V/nD for zero thrust.

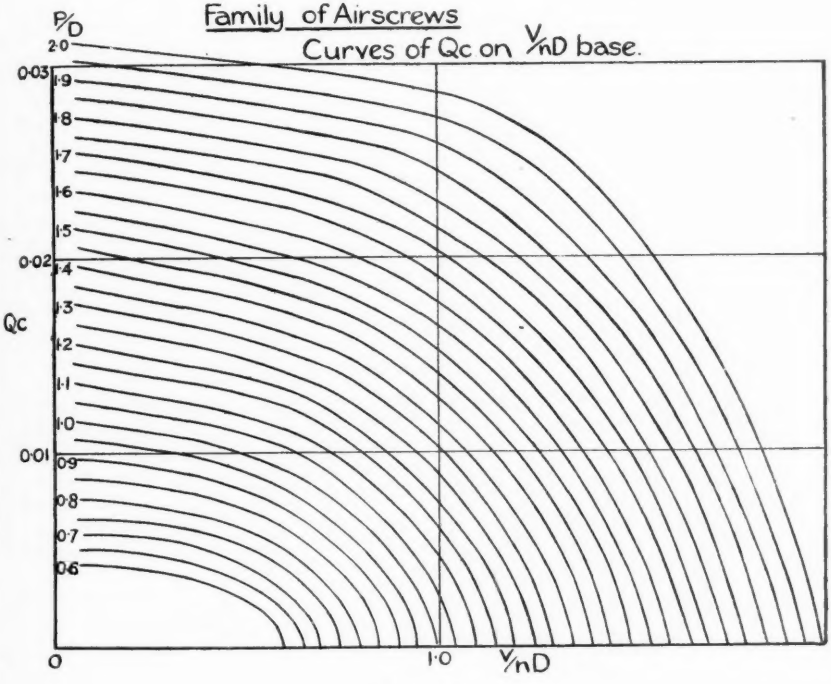


FIG. 15.

(A) *Cruising conditions.*—Let it be supposed that airscrews of this family are fitted to engines such as the Napier Lion (L.C.) whose performance characteristics are given in Fig. 17. The gear ratio of the Napier Lion is a reduction of 29 to 44, but it does not follow that this ratio will be the most suitable for every type of design, so that for the present investigation it will be supposed that the value of this ratio can be chosen to the best advantage. The loss of energy in the gears is small and usually lies between 2 and 3 per cent., and these losses should not vary appreciably with alteration in the gear ratio over the range considered.

At cruising, the value of V/nD is (since n=1850r/60 and taking V as 100 m.p.h.)

$$7.2\, Vr_0/nD \,.\, D \,.\, r \quad . \quad . \quad . \quad . \quad . \quad (36)$$

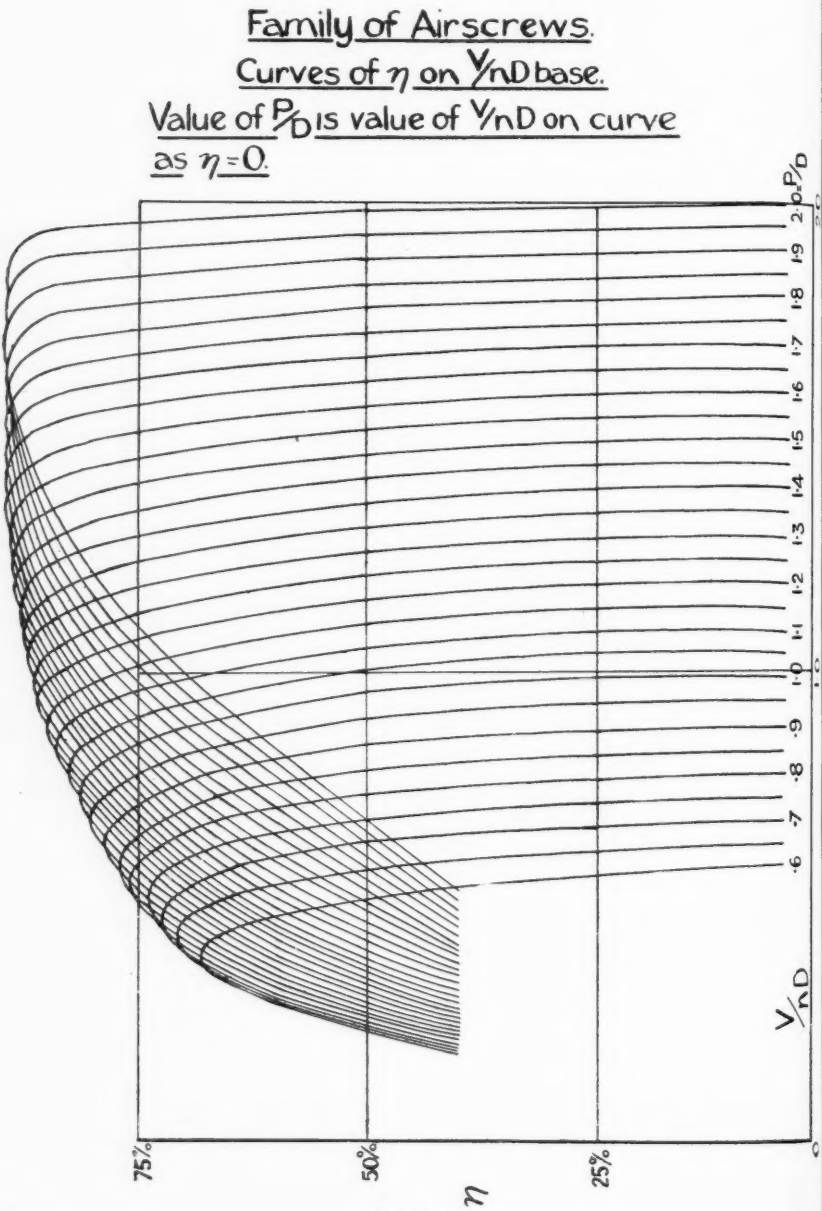

Family of Airscrews.
Curves of η on V/nD base.
Value of P/D is value of V/nD on curve
as η=0.
P/D
2·0
1·9
1·8
1·7
1·6
1·5
1·4
1·3
1·2
1·1
1·0
·9
·8
·7
·6
V/nD
75%
50%
25%
η

FIG. 16.

where r is the gear ratio and r_0 the value used in the Napier Lion, viz., 0.66. The maximum power that must be developed at cruising will be taken at 300 h.p. and the speed of the engine 1850 r.p.m. Since the power of the engine must equal the torque h.p. of the airscrew divided by the gear efficiency, the airscrew torque coefficient will be

$$Q_c = (1300 / D^5)\,(r_0/r)^3 \qquad . \quad . \quad . \quad . \quad (37)$$

From these formulæ the values of Q_c and V/nD can be found for various values of r and D, and finally with the help of Fig. 17 the values of P/D can be obtained

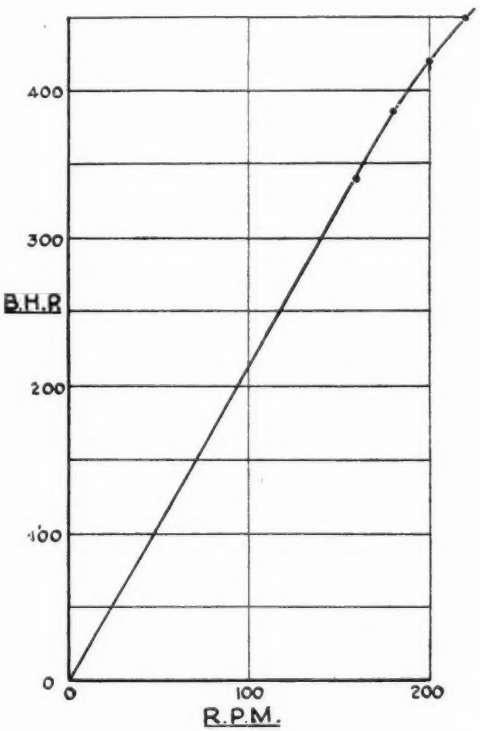


FIG. 17.

which give the required torque coefficients corresponding to the values of V/nD. The results so obtained are given in Table 12 and the efficiencies are plotted in Fig. 18. In Table 12 are also given the tip speeds for the various airscrews as a guide to an estimate of the centrifugal stresses and compressibility effects.

The curves in Fig. 18 show that over the range considered the highest efficiency is obtained for an airscrew of 16ft. diameter corresponding to a P/D ratio of 1.22 and a gear ratio of 0.33 which is about half that normally employed. This is equivalent to increasing the thrust h.p. by 9 per cent. over and above

that of the most efficient airscrew that can be obtained from this series for a normal gear ratio of 0.66. The latter airscrew is about 11ft. in diameter and has a P/D ratio of unity.

TABLE 12.

D ft.	V/nD	Q_c	P/D	η	Tip Speed ft./sec.	Taking off Thrust (lbs.)	Taking off H.P.
			$r=0.8$				
8	0.745	0.0225	1.69	64	510	1070	422
9	0.660	0.0125	1.19	72	570	1360	404
10	0.595	0.00737	0.90	76	637	1600	386
11	0.542	0.00458	0.75	75	700	1610	364
12	0.495	0.00296	0.63	65	762	1670	340
			$r=0.66$				
9	0.800	0.0223	1.70	70	574	1170	428
10	0.720	0.0131	1.20	76	637	1440	411
11	0.654	0.00816	1.00	78	702	1650	394
12	0.600	0.00528	0.81	75	765	1750	376
13	0.554	0.00353	0.70	67	829	1740	358
14	0.515	0.00245	0.61	52	892	1180	338
			$r=0.5$				
10	0.950	0.0302	2.05	66	485	1060	430
11	0.864	0.0188	1.58	77	532	1340	414
12	0.792	0.0121	1.25	81	582	1580	398
13	0.732	0.0081	1.02	81	630	1790	382
14	0.678	0.00563	0.88	76	680	1900	366
15	0.633	0.00398	0.77	69	730	1920	349
16	0.594	0.00288	0.70	61	778	1880	331
			$r=0.33$				
13	1.11	0.0283	2.02	74	414	1260	417
14	1.03	0.0196	1.68	81	445	1470	402
15	0.96	0.0139	1.42	84	476	1660	385
16	0.90	0.0100	1.22	85	510	1880	368
17	0.85	0.0074	1.07	82	540	1960	352
18	0.80	0.00556	0.96	74	572	2080	334
19	0.76	0.00425	0.87	64	605	2130	317
20	0.72	0.00329	0.80	56	638	2080	301

A further advantage will be obtained by using the larger diameter airscrew in that the effect of the slipstream will be smaller. The extra drag due to slipstream will be practically inversely proportional to the airscrew disc area. If therefore the slipstream effect for the 11ft. diameter airscrew is equivalent to decreasing the efficiency from 78 per cent. to 72 per cent. (that is, equivalent to 18 drag h.p. for an engine output of 300 h.p.), then for the 16ft. diameter airscrew only half of this drag h.p. will be produced and the airscrew efficiency might be regarded as 82 per cent., equivalent to increasing the useful thrust h.p. by 14 per cent.

Disadvantages of the larger airscrew are (*a*) the decrease in clearance between the blade tips and the ground or the necessity of heightening the undercarriage to produce sufficient clearance, and (*b*) the increased weights of gears and airscrew. As regards the former, there appears to be sufficient ground clearance in present-day commercial aircraft to allow of a fairly large increase in airscrew diameter. The latter effect, viz., that due to the increased weight, should be more than counterbalanced by the increased thrust h.p. obtained. For multi-engined machines the increase in airscrew diameter might result in a considerable increase in lateral moment of inertia of the machine due to the extra spacing of the engine nacelles.

(B) *Taking-off conditions.*—An important feature of an airscrew is that it should produce a very large thrust during the taking-off run from the aerodrome. The thrust of the airscrew is given by

$$\text{Thrust} = (550\,\eta\ \text{h.p.}/V) \times 0.98 \quad . \quad . \quad . \quad . \quad (38)$$

where h.p. is the full power for the engine at the speed of rotation for which the torque h.p. of the airscrew is equal to the engine h.p.; and the torque coefficient by

$$Q_c = (550\ \text{h.p.}/2\pi\rho D^5 n^3) \times 0.98 \quad . \quad . \quad . \quad . \quad (39)$$

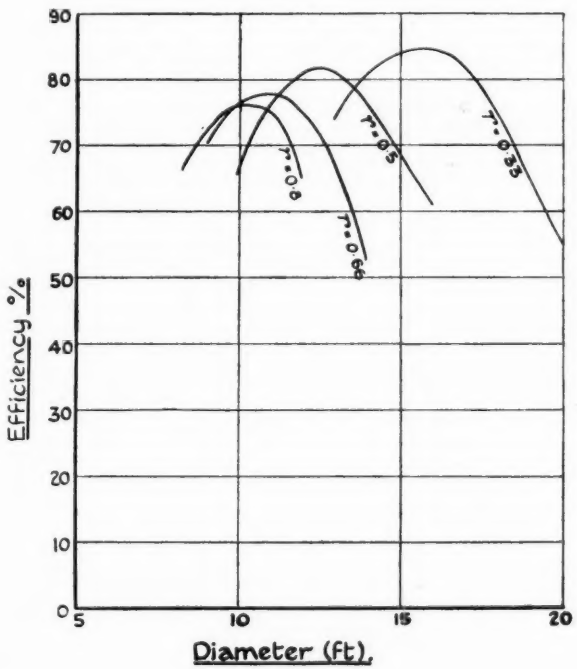


FIG. 18.

By assuming a series of values of V/nD, say, 0.1, 0.2, 0.3 and 0.4, the torque coefficients of each airscrew in Table 12 can be found over this range from Fig. 15. For a series of values of engine speed $= 60n/r$ the torque coefficient can again be found for each airscrew using the b.h.p. chart, Fig. 17, for the throttle fully opened. By plotting the latter coefficients the values of n and h.p. corresponding to each coefficient in the first set can be deduced. From the values of V/nD and these values of n, both η and V can be calculated and finally the

thrust by using the values of h.p. already obtained. By assuming the engine torque constant the work can be greatly shortened.

Calculations carried out by this method showed that for the group of airscrews chosen in Table 12 the thrust in all cases remained almost constant from zero airspeed up to about 35 m.p.h. The airscrew performances at the take off therefore may be compared from the average thrust values over this range, that is, from $V/nD=0$ to $V/nD=0.3$. These averages are given in Table 12 and plotted in Fig. 19.

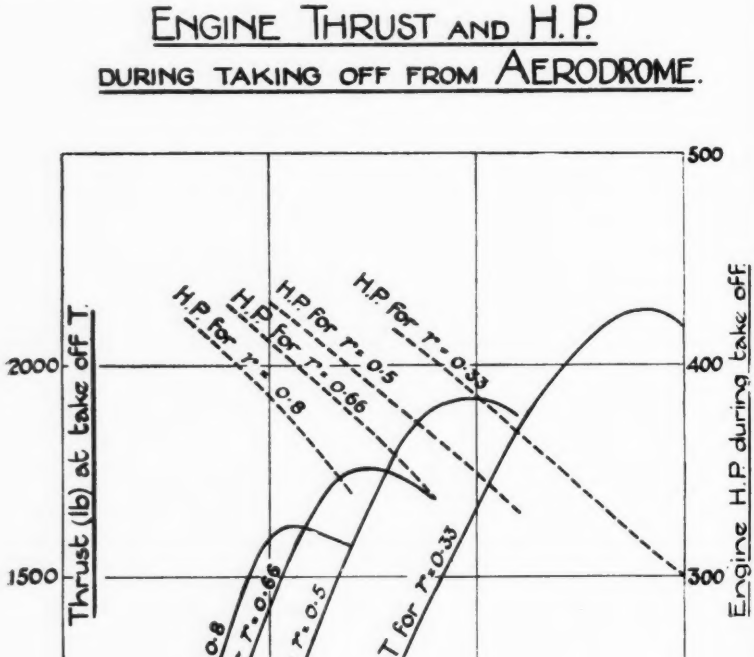


FIG. 19.

The curves of Fig. 19 show that the thrust during taking off can be increased by increasing the diameter and decreasing the gear ratio r and that for the most efficient airscrew at cruising with a gear ratio of 0.33, viz., 16ft. diameter, the thrust at the take off is about 15 per cent. greater than that for the most efficient airscrew for a gear ratio of 0.66, viz., 11ft. diameter. This thrust, however, is about 15 per cent. less than the maximum that can be obtained with a gear ratio of 0.33, but the efficiency of the airscrew at cruising for this maximum thrust is very low.

The effect of a change in airscrew on the maximum rate of climb can be estimated by supposing that the thrust remains practically constant from zero airspeed to 35 m.p.h., and above 35 m.p.h. the departure from this law will be to the advantage of the airscrew having the highest efficiency at cruising. From Table 12 it can be concluded, therefore, that the rate of climb should be better with the 16ft. airscrew for $r=0.33$ than for any airscrew having $r=0.66$.

From an inspection of the column giving the h.p. developed during taking off it will be seen that a little extra thrust can be obtained by using a variable pitch airscrew. For the engine to develop its maximum h.p., viz., 450 h.p. at 2200 r.p.m. at taking off, the torque coefficient of the airscrew will be

$$Q_c=344/r^3D^5 \quad . \quad . \quad . \quad . \quad . \quad (40)$$

From Fig. 15 the P/D ratio to give this coefficient at low values of V/nD can be found and the thrust deduced from formula (38) above. Thus for the 16ft. diameter airscrew with a gear ratio of 0.33 the thrust at taking off could be increased by 38 per cent. if the pitch/diameter were decreased to 0.87. This airscrew in fact would develop about 57 per cent. more thrust at taking off than an 11ft. airscrew having a fixed pitch and a gear ratio of 0.66. The increased weight of airscrew and gear and the added weight of the varying pitch mechanism would act to the disadvantage of that airscrew, but the gain in efficiency at cruising and in the thrust at taking off should more than compensate.

Questions such as the design of the airscrew are independent of the size of the machine, or of the route over which the machine must operate. Several important questions are interconnected with route itself both from a geographical and a meteorological point of view. In the former may be included the problem of the most economic length of stage and in the latter the effect of head winds upon design.

Economic Length of Flight Stage

In mapping out an air line of several thousand miles' length it is useful to know how the route can be most efficiently cut up into stages independently of geographical considerations. The latter are not of secondary importance, however, as the positions of certain towns must, in the main, fix the positions of certain aerodromes, but occasions may arise where several routes could be chosen having equal advantages from the point of view of traffic, but one route, on account of the lengths of its stages, would be most economical. The following investigation is an attempt to study the effect upon economy of varying the length of a flight stage: since the subject in all its practical aspects is exceedingly complex, it only seeks to put forward a skeleton analysis and to act as a starting point for discussion.

Data for the analysis have been taken from the estimates of the C.A.A.B. Report given in Table 1. It is supposed that these estimates apply to a route having four stages 350 miles in length and with a service consisting of one machine of the D.H.34 type flying each way per day at a speed of about 100 miles per hour. It will be assumed that through traffic only has been considered in the estimates, *i.e.*, the full load taken off one machine at the end of one stage is placed on the machine for the next stage.

Under the heading of Capital Cost in Table 1 entries appear such as cost of seventeen machines and seventeen engines. If this number of aeroplanes is required for a London-Constantinople route with four 350 miles' stages, there is no reason why, with the same commercial load per machine, the same number should not be required with a different number of stages, unless, for very short stages, it is found best for organisation purposes to have at least one machine in reserve at each landing ground. It will be assumed that this extreme case does not arise, and as a fairly good approximation the total number of machines

for the whole route will be taken as a constant: then the number of machines charged to each stage will be proportional to the length of stage, other factors remaining the same.

This, of course, applies to through traffic only. If the stage connects two important towns a local traffic will be set up and conclusions must be modified. A most economical length will be found for through traffic and another for local traffic, and it might reasonably be supposed that the optimum length for mixed traffic will lie between these two. The present investigation will therefore treat the two extreme cases, viz., (1) through traffic only, and (2) local traffic only.

The route for which the estimates of Table 1 were made was supposed to have an aerodrome at each end, with facilities for handling traffic, such as road transport from the aerodrome to the nearest town, and three intermediate aerodromes whose main function was to supply petrol to incoming aeroplanes and where the handling of traffic is practically negligible. Half the charge of the latter aerodromes must be placed to each stage adjoining it. If all four stages are to be regarded as equal, a terminal aerodrome would be half the cost of an intermediate aerodrome. Each terminus, however, will be more costly than each intermediate aerodrome owing to centralisation of offices and the handling of traffic. The difference between the cost for a terminal aerodrome and half the cost of an intermediate aerodrome will be termed the terminal cost T.

Let S be the cost of a stage between two non-terminal aerodromes, then the quantities to be determined are:—

1. (*a*) Cost of one stage for through traffic only at both ends = S.
   (*b*) Cost of one stage for through traffic only at one end = S + T.
2. Cost per stage for local traffic only (a terminus at both ends) = S + 2T.

In the present instance the following terminal charges have been estimated from Table 1:—

(A) Capital Costs:—(5) Transport vehicles; (6) Freight and passages of personnel to bases, and (7) Working capital in all contribute £24,000 to 2T (the two termini) out of a total of £165,500, and the remainder is divided equally between the four stages.

(B) Running Costs:—(2) Staff contributes £4,000 to 2T out of a total of £39,900 for that item; (3) Renewals, repairs and upkeep increase 2T by £500 on account of rent; and (5) Insurance increases this quantity by £3,500.

It now remains to determine how the charges left over after deducting the extra terminal charges (2T) vary with length of stage. That is, writing the total charges for the whole route as $4S_0 + 2T_0$, to determine how S_0 the yearly cost of a stage of 350 miles' length for through traffic only will alter when the stage lengths are made x miles long.

A study of this variation brings in four factors—L/L_0 the ratio of the commercial load carried by a machine in a stage of x miles to that for a stage of 350 miles; t/t_0 the ratio of the times of the journeys; w/w_0 the petrol consumption ratio, and T/T_0 the ratio of the traffic or ton-miles for the two stages.

In comparing stages the total load (tons) carried a year must be taken as constant. This means that the number of flights per day will alter with length of stage if the commercial load alters. The objection might be raised that no meaning can be attached to the flight of a fractional part of a machine, but it is assumed that this can be overcome by modification in the timetable. In the general question, however, there is no reason to suppose that the traffic available would not be more suited to a regular daily service on a line using one class of machine than on a line using another.

Further, it will be assumed that aeroplanes and engines, pilots and mechanics, have the same ratio of working time to idle time throughout the year for all

stages. Thus if one stage takes three hours for the flight and another $3\frac{1}{2}$ hours, it is not reasonable to suppose that the hours of duty per year for the pilots will follow this ratio, but rather that the number of flights per year will be in the inverse ratio and the total flying time remain the same. The same argument applies to the running of the machines and in consequence to costs of renewals, depreciation, insurance of aircraft, etc. All these costs, therefore, will vary as the product

$$(t/t_0)\,(L_0/L)=K_1 \quad . \quad . \quad . \quad . \quad . \quad (41)$$

The ratio L_0/L enters because, if the load carried in one stage per machine differs from that of another, the number of machine flights per year and consequently, for example, the number of pilots employed by the line must increase as the inverse of this ratio in order that the total load carried may remain the same.

The yearly cost of petrol depends upon the weight of petrol consumed per trip as well as upon the factor K_1 above. This item, therefore, must be altered in the ratio

$$K_2=(t/t_0)\,(L_0/L)\,(w/w_0) \quad . \quad . \quad . \quad . \quad (42)$$

One other item needs special consideration and that is (7) Sundry expenses (including general expenses, publicity, advertising, etc.). It might be supposed that the major portion of this cost is proportional to the total air ton-miles of commercial load for the full journey since advertisement, etc., would grow approximately in proportion to the income (and therefore air ton-miles) of the line. This cost will be taken to vary as

$$T/T_0=x/350=K_3 \quad . \quad . \quad . \quad . \quad . \quad (43)$$

An analysis of the expenses under (7) suggested that about 3/4ths of this item in table (1) would vary in this way.

In the table below are given the laws of variation of the different cost items with the quantities K_1, K_2 and K_3.

TABLE 13.

		Single Stage.	Extra for Terminus.
		£	£
Capital Costs		$1{,}250+34{,}125K_1$	12,000
Running Costs			
	(1)	$6{,}308K_2$	
	(2)	$1{,}550+7{,}425K_1$	2,000
	(3)	$1{,}650+2{,}725K_1$	250
	(4)	$9{,}260K_1$	
	(5)	$962+7{,}268K_1$	1,925
	(6)	1,750	
	(7)	$625+1{,}870K_3$	
Interest		$73+2{,}049K_1$	720
		$6{,}610+28{,}727K_1+6{,}308K_2+1{,}870K_3$	4,895

To calculate the three ratios K_1, K_2 and K_3 it may be supposed that the petrol consumption per mile at any instant is proportional to the weight of the machine at that instant. If w be the total petrol consumption for a journey of length x and w_0 the weight of machine at the beginning of the trip, then

$$\alpha\,(w_0-w)=dw/dx \quad . \quad . \quad . \quad . \quad . \quad (44)$$

where α is a constant, giving $w/w_0=10.2\,(1-e^{-\alpha x})$ for the standard machine. The constant α, found from the consumption figure of 687lb.* of fuel for 350 miles journey works out as 2.95×10^{-4} in miles units.

* This figure was originally adopted to meet the average requirements of the route, such as allowance for flight against head winds, etc.

From this value of w the commercial load factor can be obtained from $L/L_0=(2547-w)/1860$. On the supposition that flight always takes place at the position of maximum L/D, the speed of flight will be proportional to the root of the machine weight and the time factor will be

$$t/t_0=(e^{ax/2}-1)/0.052 \quad . \quad . \quad . \quad . \quad (45)$$

Using these factors, Table 14 is obtained. This table gives the cost per ton-mile for various lengths of one stage of the type 1*a* and also the amount to be added to this figure if a terminus be included. The maximum length of stage of this type of machine when carrying petrol and oil in place of commercial load is 1520 miles.

TABLE 14.

Length of Stage, x mls.	Petrol Consumption, w lb.	Commercial Load per Machine, L lb.	Machine ton-miles.	Yearly ton-miles.	Yearly Cost per Stage (no terminus). £	Stage Cost per ton-mile pence.	Cost of Terminus per ton-mile pence.
100	205	2342	105	69,200	11,716	41.0	17.0
150	304	2243	150	103,700	16,640	38.6	11.3
200	404	2143	191	138,200	22,040	38.4	8.5
250	502	2045	228	173,000	28,340	39.2	6.8
300	596	1951	262	207,500	35,460	41.2	5.7
350	687	1860	290	242,000	43,510	43.0	4.9
400	780	1767	316	276,500	54,850	47.6	4.2
500	965	1582	354	346,000	82,430	57.0	3.4
1520	2547	0	—	—	—	—	—

In Fig. 20 are plotted three curves corresponding to the cases 1(*a*), 1(*b*) and 2 above, viz., cost per stage for through traffic, cost per stage without terminus and cost per stage with one terminus; and for local traffic cost per stage with two termini.

This diagram shows that the minimum cost per ton-mile for case 1(*a*) occurs at a fairly short length of stage, viz., 180 miles, and that the variation in economy over a range of 50 miles on either side of this optimum is very small. The introduction of a terminus to a stage increases the length for maximum economy to 250 miles (case 1(*b*)) and two termini increases this length to 300 miles (case 2). In both these cases the variation in economy over a range of 50 miles on either side is slight.

The length of stage for maximum efficiency appears to be fairly short, but probably this is to be expected in view of the immense effect upon economy of alteration in the commercial load of the machine. This load in D.H.34 is at the very best only 1,860lb.* with a petrol and oil consumption of 867lb. for a 350-mile stage, and it is not surprising to find that an increase in the former obtained by decreasing the latter is conducive to greater economy.

A short length of stage, although acting as a loss as far as the question of time for the total journey is concerned, has a few marked advantages. In the first place the reliability factor of the service is increased, chiefly on account of the fact that the engine and machine can receive more inspections over the full route. Another advantage is that an increase in the number of descents will decrease the monotony of the journey and again increase the reliability factor through decreasing the fatigue of the pilot. The short stage also brings more towns into the line and increases the possibility of more traffic.

* This figure was obtained from the type test reports of the Air Ministry, but modifications to the machine have since reduced this to 1,450 lb.

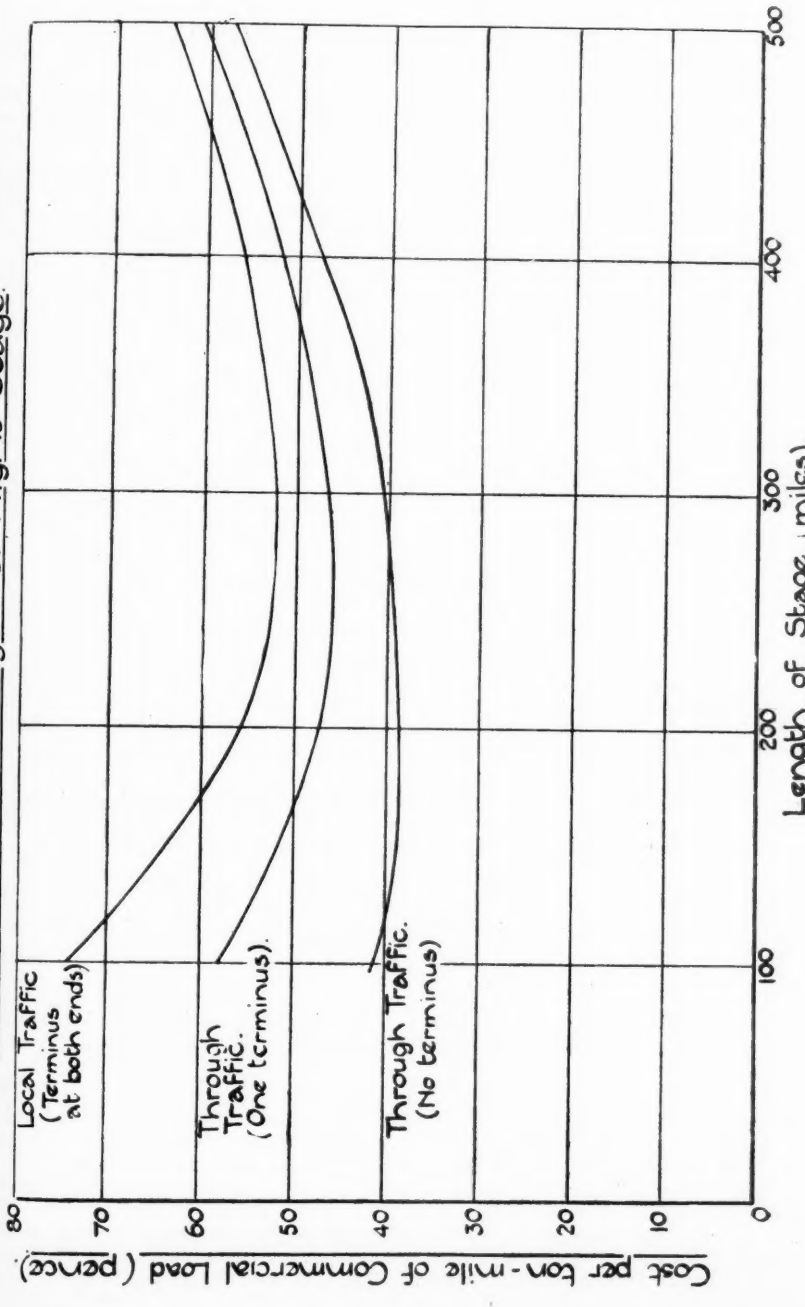

Most Economical Length of Flight Stage.
Local Traffic (Terminus at both ends)
Through Traffic. (One terminus).
Through Traffic. (No terminus)
Cost per ton-mile of Commercial load (pence).
80
70
60
50
40
30
20
10
0
100
200
300
400
500
Length of Stage (miles).

FIG. 20.

*The Wind Factor in Flight**

The effect of wind plays an important part in flight chiefly in the fact that it is practically equivalent to increasing the length of stage.

If it is desired to design a machine so that it is possible to complete the journey in all types of wind, the fuel capacity must be considerably increased. This will in turn decrease the paying load of the machine considerably and although in a following wind less petrol need be carried, the saving in weight that would result could not be utilised, on the average, for increasing the carrying capacity of the machine. Thus, since, in general, an air line must carry the same amount of traffic each way, it follows that the commercial load will, on the average, be the same whether the flight is made with or against the wind. The economic effect of a following wind is practically equal to the direct financial gain due to a lower fuel bill plus the gain resulting from the saving in the time of flight, but such a wind has no effect upon the question of the commercial load which the machine is designed to carry.

From the point of view of reliability of service, the ideal condition is to allow sufficient carrying capacity for fuel so that it would be possible to complete the journey against the strongest head winds. Economically, however, this is not advisable as during a severe storm a flight may be cancelled irrespective of whether or not sufficient petrol could be carried for the journey. It would prove interesting, therefore, to determine the effect upon economy of cancelled flights and to see how costs are modified by designing the machine so that flight can only be allowed if the wind speed does not exceed a certain value.

It will be supposed in the investigation that if a flight is cancelled, the traffic concerned will be lost to the service and that if flight is not permitted one way on account of excessive head wind the flights in the opposite direction must also be cancelled because although a following wind exists in these cases and the complete journey is possible with the petrol carried, one way flight would cause the accumulation of machines at one end of the line with consequent disorganisation. Having fixed upon the extreme case, that is, having decided that all flights must be cancelled if head winds in either direction exceed a certain speed, the maximum fuel consumption per trip can be found and the commercial load deduced.

Let p = petrol weight for extreme condition of flight; a head wind say of v m.p.h.

p_o = petrol weight for the standard case, that is for $v = O$.

Then

$$p = p_o V/(V - v) \quad . \quad . \quad . \quad . \quad . \quad (46)$$

where V is the cruising speed of the machine, and the commercial load will be

$$w = w_o + p_o - p \quad . \quad . \quad . \quad . \quad . \quad (47)$$

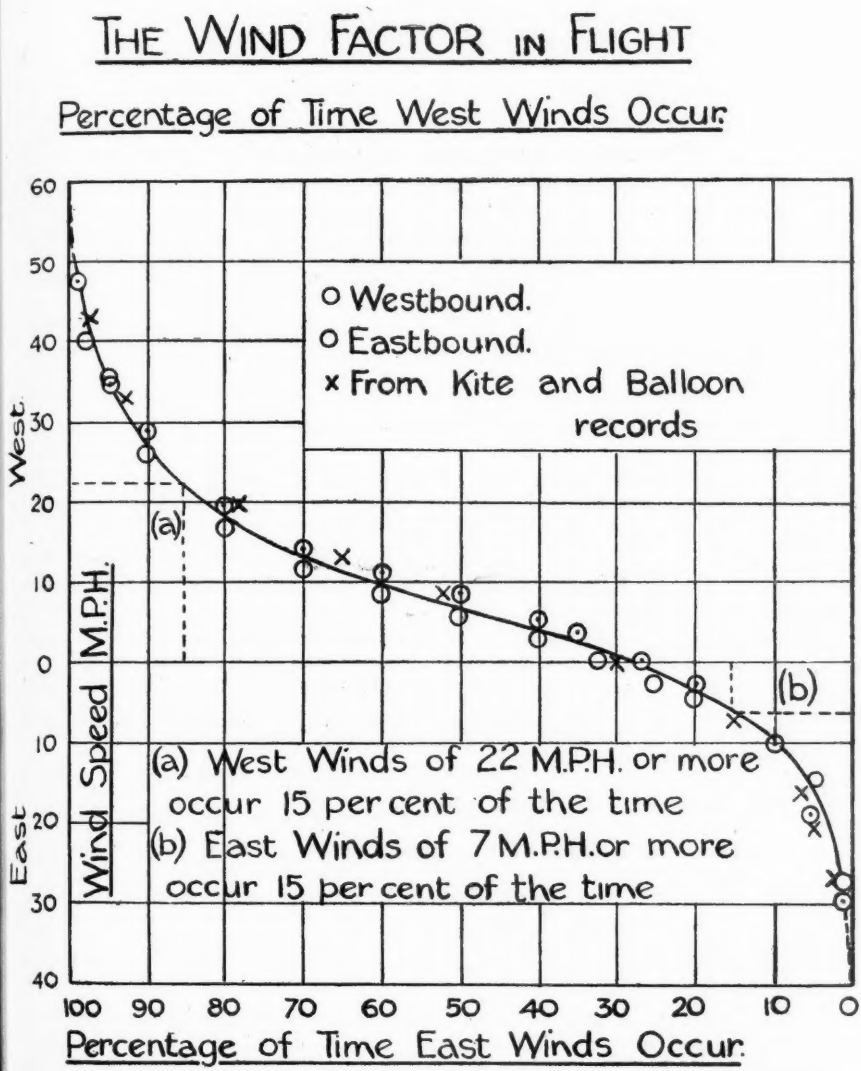
where w_o is the load for zero wind.

If all flights for the day must be abandoned when the wind exceeds v m.p.h., viz., n flight per year as a fraction of the total flights, the loss in fares per ton-mile will be

$$F \times K \times n \quad . \quad . \quad . \quad . \quad . \quad (48)$$

where F is the fare per ton-mile and K the fraction of the fare lost on each abandoned trip. By assuming that the costs for depreciation, repairs, petrol, etc., are not losses in this respect, but expenses that are not incurred in a cancelled trip and that wages and overhead charges must be paid whether the flight is made or not, the value of K from Table 1 would be about 0.6. The altered carrying capacity of the machine will effect the takings in the inverse

* See "Fuel Economy in Flight," by H. T. Tizard, in the Wilbur Wright Memorial Lecture for 1925.



Annual percentage occurrence of East and West winds of different speeds along the New York Chicago route.

Cruising speed of machines approximately 93 m.p.h.

FIG. 21.

ratio to the commercial load, so that to all practical purposes the new fare F will be apart from variation in other operation costs,

$$F = F \times 0.6\, n + F_o w/(w + p_o - p) \quad . \quad . \quad . \quad (49)$$

where F_o would be the fare for no wind.

This reduces to

$$F/F_o = (1 - v/V)/\{1 - (1 + a)\, v/V\} \times 1/(1 - 0.6\, n) \quad . \quad . \quad (50)$$

where a is the ratio of the petrol weight to the commercial load in the standard case here assumed, viz., for no wind.

The value of n will be taken as that found from the analysis of one year's records of the American Air Mail Service*. This is given in Fig. 21, the results being deduced from kite and balloon records as well as actual flight for a height of about 1,500ft.

By assuming various values of v/V for $V = 95$ m.p.h. the values of F/F_o can be found from the above formula. This, however, takes into account only two factors, viz., the effects of alteration in commercial load and cancelled flights. A considerable effect upon costs might result from the increase in the fuel bill for general working together with the influence of the time factor upon pilots' wages, depreciation, repairs, etc.

This effect can be allowed for approximately as follows:—

The number of flights that occur between winds of v and $v + dv$ as a fraction of the total flights that would occur for no wind is

$$(dn/dv)\, \delta v \quad . \quad . \quad . \quad . \quad . \quad . \quad (51)$$

For each pair of flights, that is travelling against the wind and returning, the time taken will be

$$V/(1 - V) \text{ and } V/(1 + v) \text{ respectively,} \quad . \quad . \quad . \quad (52)$$

so that the time in excess of that for no wind will be for the flights in (51)

$$(2\, v/V)/\{1 - (v/V)^2\} \quad . \quad . \quad . \quad . \quad (53)$$

Assuming that 0.6 of the costs are affected by the time factor the increased costs will become

$$1.2 \int (v/V)/\{1 - (v/V)^2\} \,.\, (dn/dv)\, dv = 1.2 \int (v/V)/\{1 - (v/V)^2\} \,.\, dn \quad . \quad (54)$$

This quantity can be determined from Fig. 21 by plotting $(v/V)/\{1 - (v/V)^2\}$ on the n base of that diagram for the cases concerned. A typical curve is given in Fig. 22. The various integrals over the range of v corresponding to v in (51) must be added to F/F_o. The final curve so obtained is given as factor 1.0 in Fig. 22 for a cruising speed of 95 m.p.h. The curve for very low values of v is in error because the cost relationships in Table 1 would cease to hold. As v tends to zero the value of K in (48) will tend to unity so that the curve will become asymptotic to $v = 0$.

The curve shows that the wind increases the costs or fares by a minimum of about 30 per cent., and if the machine were designed to overcome all winds the costs would be increased by about 60 per cent. On the diagram the position is indicated (AB) corresponding to that of the standard machine of Table 1, and it will be seen that the costs for this machine are not much in excess of the minimum.

No account has been taken in this analysis of the effect on economy of the alteration in reliability due to cancelled flights. From Fig. 22 it will be seen that, for the case taken for the standard machine, about 5 per cent. of the time

* "The Wind Factor in Flight: An Analysis of One Year's Record of the Air Mail." By Willis Ray Gregg, Meteorologist, and Lieut. J. Parker Van Zandt, United States Air Service. U.S. Dept. of Agriculture, Weather Bureau, Washington, D.C., April 27th, 1923.

EFFECT OF WIND ON COSTS.

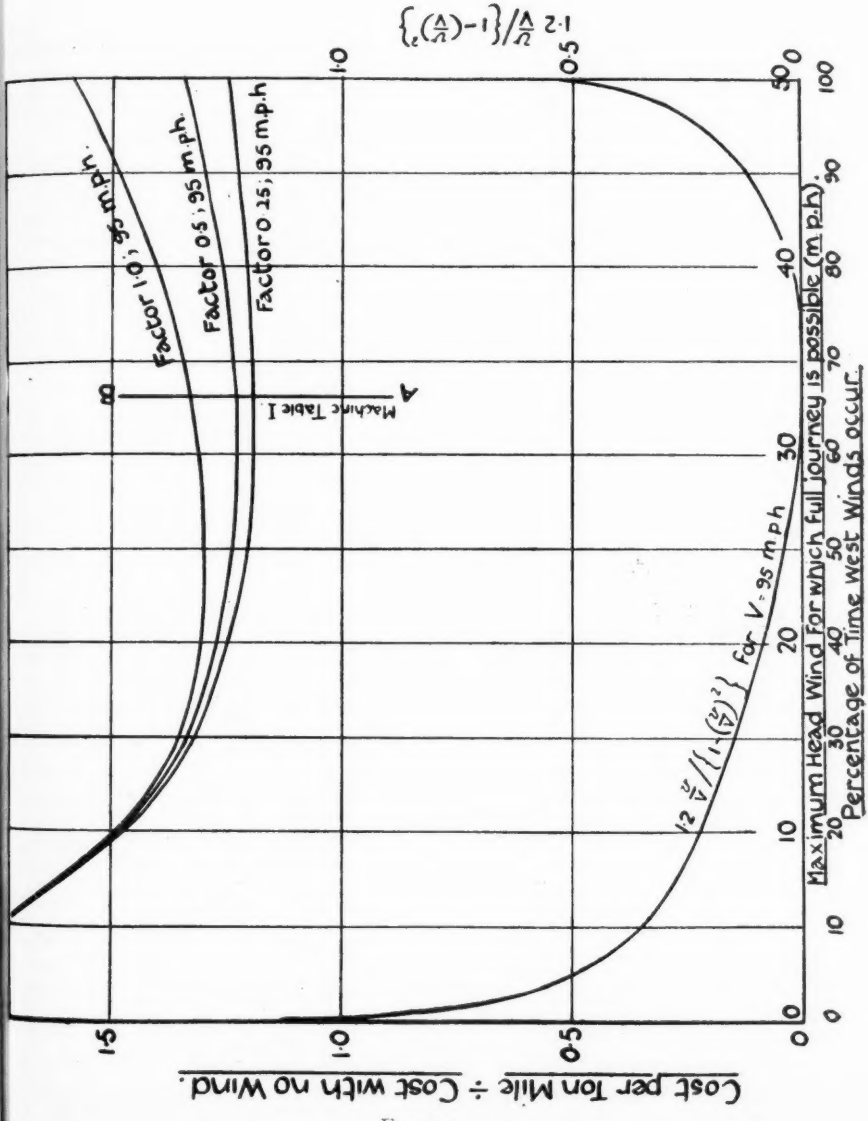

Factor 1·0; 95 m.p.h.
Factor 0·5; 95 m.p.h.
Factor 0·25; 95 m.p.h
Machine Table I
A
Maximum Head Wind for which full journey is possible (m.p.h.)
Percentage of Time West Winds occur.
Cost per Ton Mile ÷ Cost with no Wind.

FIG. 22.

must be cancelled for flight, whereas on the Continental services this is decreased by the introduction of an intermediate fuelling station.

Further, it has been assumed that any increase in petrol must be counterbalanced by an equal decrease in commercial load. This is not strictly true, and from the investigation on the most economical size of machine it would appear to be nearer the true condition to suppose that only 25 per cent. of the increased petrol weight must be deducted from the commercial load. On this assumption the curve for factor=0.25 is obtained. In this case the line AB is nearer the minimum which is now only 20 per cent. greater than the fare for no wind. An increase of only 5 per cent. in fare would result if a design were evolved to overcome the strongest winds considered. For freight-carrying machines the factor will be nearer unity than 0.25 because the spaces required for equal weights of fuel and freight will be about the same.

The advisability of building machines only for freight carrying to the Continent is now receiving attention in this country, and it is considered that, for such machines, if a lower cruising speed be allowed together with an intermediate fuelling station between London and the main Continental centres, freight could be carried at a much cheaper rate than at present.

To study this question, it may be supposed that the cruising speed is varied by altering the wing area and that the total weight of the machine for the various cruising speeds is given by the upper curve of Fig. 13. From this the extra load carried can be found (Fig. 13) and the cost per ton-mile for the case of zero wind from Fig. 14, curve (A).

As an intermediate fuelling station is to be allowed, the flight stage may be supposed to be half the length of the original. Further, for freight-carrying machines the space required for extra fuel tanks will be about equal to the space occupied by the same weight of commercial load. From these two conditions, the value of α in (50) will be about half the value used in calculating the curve marked factor 1.0 in Fig. 22. Thus the relative costs for various values of z the maximum wind speed will be as given by the curve marked factor 0.5 in Fig. 22 for a cruising speed of 95 m.p.h.

The effect of varying the cruising speed V by varying the wing area is shown in Fig. 23. In this diagram the factor α varies from curve to curve because both the fuel consumption and the commercial load vary between the standard conditions of no wind. The value of the unit of the ordinates of these curves can be deduced from curve (A), Fig. 14, mentioned above. The final costs found in this way and expressed as ratios of the costs for a cruising speed of 95 m.p.h. are also given in Fig. 23. It should be noted that the top set of curves of Fig. 23 are plotted with the cost for the machine flying in still air as the unit and having the given cruising speed, whereas the lower set have for the unit ordinate the cost for a machine having a cruising speed of 95 m.p.h. flying in a disturbed atmosphere represented by Fig. 21 and with flight cancelled for winds exceeding the value given by the abscissa, the stage length being about 150 miles. This set of curves in fact shows at a glance the effect of varying the cruising speed. The minimum costs are indicated by the dotted line in Fig. 23.

An inspection of the final cost curves of Fig. 23 shows that for the condition represented by the standard machine of Table 1, viz., the line AB, but having only half the stage length, the costs decrease continually even to as low a cruising speed as 65 m.p.h. where the reduction has amounted to about 25 per cent. At the position of minimum costs, viz., line CD, the reduction is about 30 per cent.

If it be desired to compare with present lines to the Continent where an intermediate fuelling station may be used under extreme circumstances, comparison must be made with the cost given in Fig. 22 for the curve factor 1.0 on the line AB, and also allowance must be made for the alteration of stage length. For

FREIGHT CARRYING MACHINES.

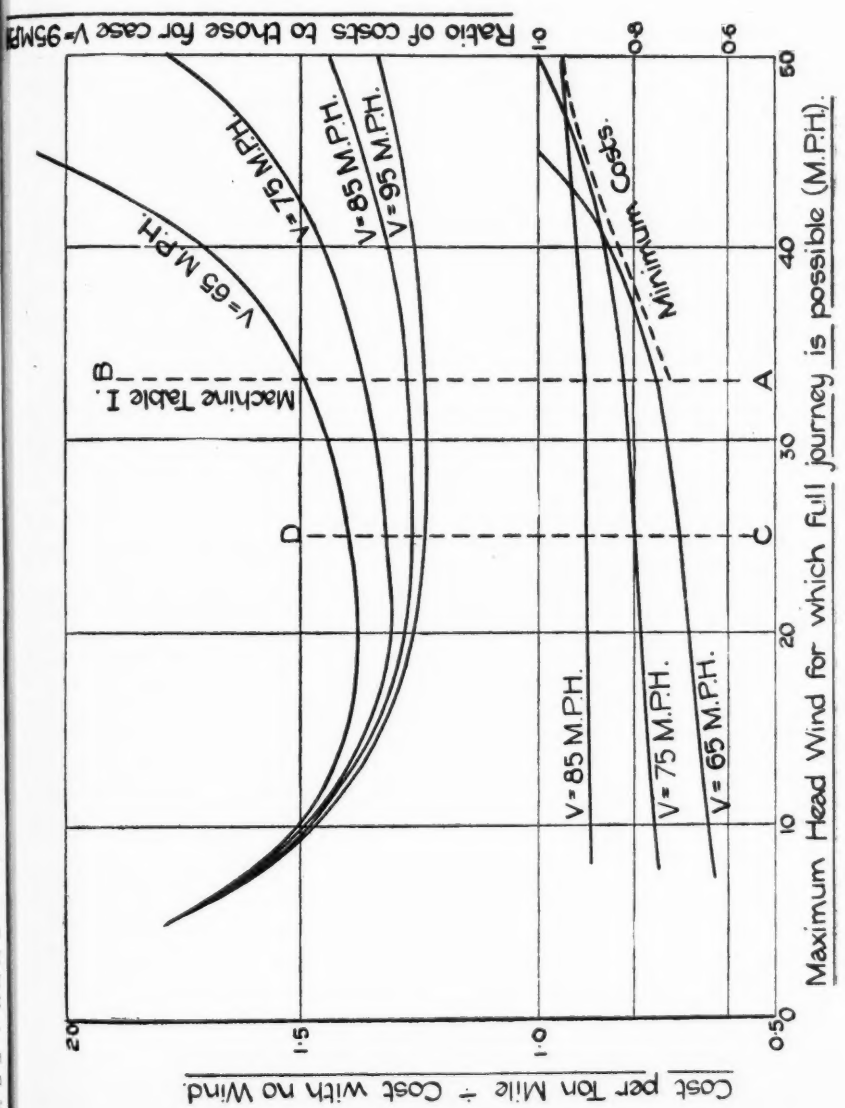


FIG. 23.

the latter purpose the middle curve of Fig. 20 may be used. To obtain equal reliability in the comparison, the standard case may be supposed equivalent to moving the line AB to the right, so that the minimum costs will lie somewhere on the dotted line given in that diagram after allowance has been made for the two effects mentioned above. After making this allowance, it will be seen that the curve of minimum costs is practically a straight line passing through unity at $v = 50$ m.p.h. and 0.65 on AB.

It is very difficult to estimate the position in which to place the line AB on the diagram to represent equal reliability. An approximate estimate has been made from records of abandoned flights on the British air lines through excessive wind and it would appear that in all probability the value of v will not be less than 45 m.p.h., so that the cost per ton-mile would not decrease by more than 10 per cent.

Conclusion

The work of the present paper has been mainly directed towards a systematic study of the subject of aircraft transport economy. Unfortunately the complexity of the subject and the lack of suitable data detracts considerably from the value of many investigations attempted. Results that are obtained must therefore be accepted with an open mind, but it is considered that the present work would prove useful in indicating which parts of the subject show promise so that in these cases more elaborate calculations based upon suitable data could be made.

As far as the present paper touches the subject it would appear that any increase in the reliability of the service during the winter months would, if it resulted in levelling out the seasonal variation of traffic, greatly increase the economic efficiency of aerial transport.

An exhaustive study should be made of structural problems, as not only would design generally be improved thereby, but the important question of the most economical size of machine could be more easily solved. With the present state of knowledge, the position is very unsatisfactory with regard to this question. Thus, statistics on the weights of aeroplane structures indicate that an increase in machine size is conducive to greater economic efficiency, but stress experts take exception to this conclusion on account of the fact that a smaller load factor is used when designing large machines and because, from theoretical stress considerations, the proportion of structure weight to the total load should continually increase with size. Whether or not the statistical investigation should be given preference is a difficult point to decide, but it is interesting to note that for engines the law of variation in weight is in the opposite direction to that demanded by the stress formulæ and that in this instance the load factor does not play such a predominant part. All statistical work points to increased economic efficiency with increased machine size.

There is little doubt that a greater reliability of service should result from using three-engined machines if flight can still be maintained with any one engine out of action. The development of the three-engined machine would naturally occur if the economical efficiency increased with size, but the increased comfort of travel and improved reliability that must result from large three-engined machines would be sufficient to justify its adoption.

It would appear from the investigation of the economic effect of increasing the engine power output at cruising that considerable economic gain would result by this means. The reliability of the line would fall in consequence, but sufficient money should be available to cover any increased cost of repairs, overhauls, etc., necessary to raise the reliability figure to its original value.

There are strong reasons to believe that considerable gain should result from altering the airscrew design together with the engine gear ratio. Limitations on airscrew diameter, etc., that play such an important part in military machines, should not be so prominent on commercial aircraft.

The effect of winds is an important factor in aircraft transport and it is necessary to economy if a reliable service is to be maintained that the cruising speed of the machine should be high enough for the machine to overcome them without too large a loss in time. A cruising speed of 95 m.p.h. as used at present appears to be fairly near the economical optimum. Even on freight machines where time is not such an important factor the most economical speed is but little below this speed. Freight machines would probably differ from passenger machines almost entirely through the smaller cabin space required for the same weight carried. The body resistance of such machines should in consequence be smaller.

In conclusion, I wish to thank the members of the Air Transport Sub-Committee and my colleagues at the National Physical Laboratory for the help they have given in the preparation of the paper.

Discussion

Mr. W. H. Sayers: Mr. Cowley is to be congratulated upon having compressed into a remarkably compact form an analysis of the effects upon the commercial performance of an aeroplane of a large number of variations in design. The questions with which he deals are important both to the aircraft designer and to the aircraft operator, but in general they cover only one section of the economics of air transport. It is true that Mr. Cowley mentions the influence of variations in traffic on costs, and suggests that measures to reduce such variations would be of very great value, but in the main he confines his attention to the aeroplane itself and methods of increasing its commercial efficiency. I cannot help feeling that too much attention has been given to this matter of improving the aeroplane and too little to the possibility of improving the air lines. It is obvious that the overall commercial efficiency of the whole operating organisation is the only factor that is of real importance and that before it is possible to assess the value of a given change in the characteristics of the aeroplane it is essential to know at least in general terms the laws which govern the total cost of a complete air transport service.

It can quite safely be asserted that in some conditions maximum overall commercial economy will be attained by the use of aircraft which, if considered on the usual basis of their actual cost of operation, could be said to be extremely inefficient machines. As an instance, it might be cheaper to buy extremely expensive machines carrying a very small commercial load per h.p. as an alternative to spending vast sums on ground organisation in order to secure the desired degree of safety and reliability.

The lack of published data as to the costs of operation of existing air lines to which Mr. Cowley refers is obviously a serious difficulty which confronts any effort to establish a general law of this kind. Fortunately, however, fragments of data have been permitted to escape at odd intervals, and by piecing these together it is possible to arrive at some idea of what the costs of existing services are.

A good deal of help can be obtained from a study of the laws governing costs in other industries. As an instance, the total costs of an electric power station are composed of items of a nature very similar to those of an air line. Thus there are salaries and wages of management and operational staff, insurance and depreciation charges, fuel and oil costs, repair and maintenance costs, and in addition, electric power stations operate under conditions of load variation

both from hour to hour and from season to season, which are at least as wide as those of the present air transport lines.

It has been shown that if the total costs in a series of periods of a given power station be plotted against the outputs for the same periods, the resulting curve is a straight line cutting the axis of zero output at some considerable distance above the axis of zero costs. The analogy between the power station and the air line is sufficiently close to lead one to believe that air line total costs, plotted against ton-miles of flying, should give a similar straight line.

The lack of data already mentioned renders it difficult to check the accuracy of this suggested straight line law. Mr. Cowley's paper in Table 2 provides one opportunity for doing this. If the monthly figure for passenger miles there given is multiplied by the monthly cost per passenger mile, the total cost for each month (expressed in terms of the average cost per passenger mile over the whole period) can be ascertained. If these monthly total costs are plotted against miles flown in that month, the points numbered 1 to 11 on Fig. A are obtained. These points are rather widely scattered, but they suggest a constant slope for the curve of total costs. This scattering is not surprising in view of the short period of one month which has been taken. The abnormally low point 8 (May), for instance, is accounted for by the rebate on insurance premiums, which obviously should be distributed over previous months. If the straight line law really holds a closer approximation to the truth will be obtained by taking periods of greater length. Dividing the eleven months into three periods of three months each and one of two months, and taking the average of each period leads to the points A, B, C and D.

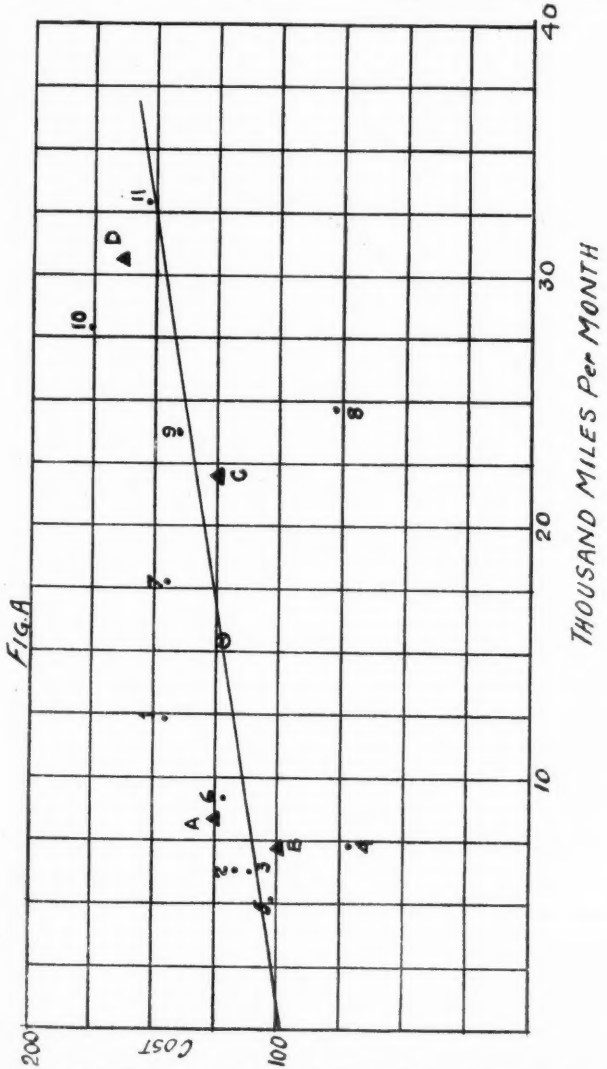
If the average over the whole period is taken, the point marked by a circle is obtained, and a straight line can be drawn through this which lies evenly between the four points A, B, C and D. It is suggested that this line gives a fairly accurate measure of the real rate of variation of costs in this instance. The evidence of this particular service is far from conclusive, but taken with the known accuracy of similar curves for analogous cases in other industries, it at least suggests that the straight line law of variation of cost can be applied to air lines with some approximation to the truth.

Unfortunately, the units in which costs are represented are of unknown value in this case, which very greatly limits the value of the curve. It is, however, obvious that the ratio of the standing charges—those corresponding to zero flying—to the extra cost of running the actual service provided is very high indeed. Taking the whole period, standing charges account for 100 out of a total of about 125, or 80 per cent. of the total.

A word of warning as to "standing" charges is necessary here. If all items usually regarded as running costs are plotted against miles flown, it will be found that they do not fall to zero for zero flying. This is obvious if it is imagined that the fleet of machines is standing in the sheds ready to run but not actually in service. Certain maintenance costs—cleaning, greasing, etc.—must nevertheless occur. Tyres, rubber shock absorbers, fabric and dope, and other components are depreciating. Petrol and oil in tanks and engine will be lost by evaporation and leakage, and may be consumed by occasional test runs on engines, etc. Thus the "standing" charges on a cost diagram of this type are always higher than the charges usually considered as overhead, and in consequence the slope of the curve is less steep than the figures usually taken as running costs would indicate.

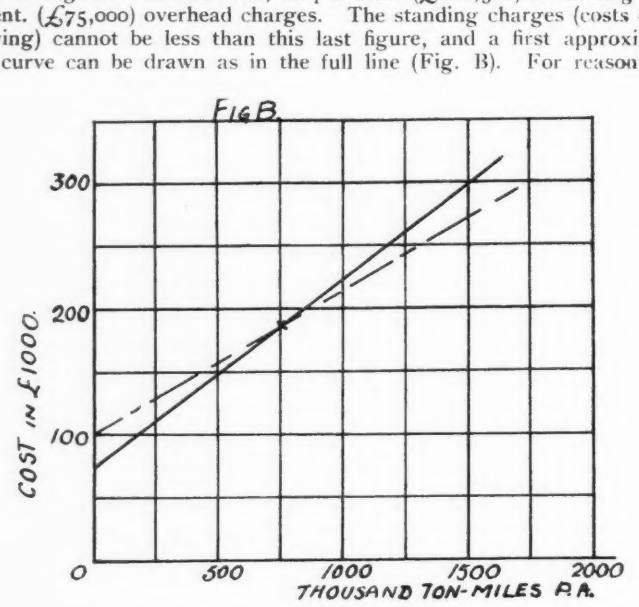
If the applicability of the straight line law of costs is accepted, the next step is to put definite values to the ordinates for known conditions. Lack of data is again the difficulty. In a recent paper Sir Sefton Brancker gave 3/- per ton-mile as the running costs and 2/- per ton-mile as the overhead charges for a particular type of machine. Obviously the overhead charges can refer only to a particular

set of circumstances, and it seems fairly obvious that the particular set of circumstances are not widely dissimilar from those obtaining on Imperial Airways. Some traffic data for this line for the year 1924-25 are available, and if it is assumed that the figures above quoted apply to the service in question, a cost curve can be constituted. Its accuracy will naturally not be very great, but it can reasonably be supposed to represent some approximation to the truth.



From published statistics of the miles flown in 1924-25 (825,000) and from the composition of the Imperial Airways fleet, it may be estimated that their total flying was the equivalent of about 750,000 ton-miles of machine capacity. Assuming Sir Sefton Brancker's 3/- and 2/- per ton-mile to apply, the total cost

per annum for 750,000 ton-miles would be £187,500, which gives one point on the curve of Fig. B. Of this total, 60 per cent. (£112,500) is running costs and 40 per cent. (£75,000) overhead charges. The standing charges (costs equivalent to no flying) cannot be less than this last figure, and a first approximation to the cost curve can be drawn as in the full line (Fig. B). For reasons outlined



above, the " running costs " for zero flying are not zero, therefore the real curve will be more like the dotted line, but as no data are available to estimate this correction, the first approximation is possibly as accurate a representation of facts as can be advanced.

(It will be understood that a curve of this nature can apply only to a fixed fleet and a fixed organisation, the service given alone being variable. Increase of fleet, changes in staff, and so forth, obviously may affect both standing charges and the slope of the running costs line, but subject to this the curve gives total costs for any intensity of service within the capacity of the organisation as a whole.)

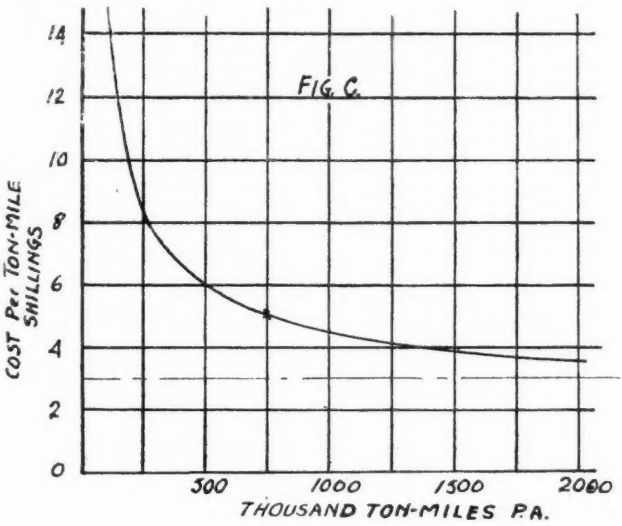
From this curve the cost per ton-mile for varying intensity of service may easily be deduced. For zero ton-miles per annum the cost per ton-mile is infinite; for infinite miles it becomes (in this case) 3/- per ton-mile, and at 750,000 ton-miles per annum it is 5/-. The actual curve of cost per ton-mile against ton-miles (capacity) flown is given in Fig. C for this assumed case.

So far only the cost per ton-mile of capacity has been considered. The actual traffic carried cannot exceed this capacity, and in practice will invariably fall below it, *i.e.*, machines cannot carry more than full load and frequently will carry less. The ratio between the capacity ton-miles of the service given and the traffic actually carried may be called the load factor of the service, and the value of this load factor is of very great importance.

Imperial Airways traffic statistics give total passengers carried and total weight of goods carried, but do not show how the traffic was divided among the various routes and stages. It can, however, be deduced that the average transport stage on this service is very nearly 200 miles, and by taking passengers with luggage as averaging 11 to the ton, the total traffic carried can be estimated at about 345,000 ton-miles—a load factor of 345/750 = 46 per cent.

This total traffic therefore bore the costs of 750,000 ton-miles capacity, and the cost of the traffic actually carried is £187,500/345,000=£.543 or 10/9 per ton-mile—or about 1/- per passenger mile. A fare of £12 per passenger London to Paris is required to cover this.

If the same total traffic could have been carried at 100 per cent. load factor —that is, if just enough machines to carry it had been run and had been filled—



the cost per ton-wile of capacity would be 7/5, but this would also have been the cost per ton-mile of traffic carried. A fare of £8 10s. per passenger would cover this.

If the actual service run had secured 100 per cent. load factor—that is, if the traffic carried had reached 750,000 ton-miles—the cost per ton-mile carried would have been 5/- and the paying fare could have been reduced to £5 10s. From these very rough figures it can be seen that very great improvements in the commercial efficiency of a given air line organisation can be secured by improving the load factors of the service. It is obvious that there are two main items involved. For a given service, costs per ton-mile capacity can be reduced by reducing the size of the fleet and making each machine fly more miles per annum. Secondly, the cost per ton-mile of traffic actually handled can be reduced by keeping the average load of the machines up to the maximum—that is, by flying the smallest service which will actually secure that traffic.

If the figures which have been used in the illustration above are even approximately accurate, it is obvious that much more is to be expected from an improvement in the load factor of existing services than from any improvement in the running cost of the aeroplanes themselves. In other words, the problem of the air lines is very much more one of getting a profitable traffic than one of obtaining machines of very low running costs. As an illustration, it may be pointed out that if the running costs of Imperial Airways 1924-25 had been zero, they would pretty certainly have made a loss in the year's working apart from subsidy.

Thus it may fairly be said that in focussing the whole of our attention on the defects of the aeroplane itself we risk losing sight of the wood for the trees.

The problem of attracting a paying traffic is a very large and complex one which cannot properly be discussed here, but it may be pointed out that under favourable conditions the traffic load factor is not entirely beyond the control of the operators. Having decided how best a reasonable traffic may be obtained, the operator still has a good deal of latitude as to the precise methods by which he should handle it when obtained.

Mr. Cowley has referred to this aspect of the problem under the heading "Relation between Machine Size and Effects of Traffic Variation," but I can scarcely accept his examination of this matter as adequate. His suggestion that six small machines in place of one large one are necessary to handle a six-to-one variation in traffic density will, I think, be recognised as exaggerated when all the conditions are taken into account. The particular case (of Table 2) suggests that smaller machines could have been used advantageously in this case. If passenger miles are divided by machine miles month by month, the average number of passengers per trip will be given. From Table 2 the following figures result :

TABLE A.

Month.	Average number of passengers per trip.	% of trips duplicated.
October	8.8	60
November	6.56	42
December	6.1	35
January	3.6	33
February	6.02	35
March	7.5	45
April	8.47	55
May	5.0	40
June	7.45	45
July	9.65	90
August	10.1	100

The average number of passengers per trip varies from 10.1 to 3.6 from month to month. The average for the whole eleven months is 7.24. It may be deduced that the machines used have a capacity of more than ten seats which suggest a fleet of twelve-seaters (presumably twin-engine type). Imagine these replaced by eight six-seaters. There is no reason to believe that such machines would be less economical than the larger types in practice except as regards the item of pilots' pay, which it may be assumed will increase in proportion to the number of machines, *i.e.*, will be doubled.

To compare the two cases it must be assumed that one small machine is run in every case where the larger type was actually used and that when the traffic exceeded the capacity of one small machine, two would be run. That is an identical service of the smaller machines is given and this service is duplicated when necessary. If this condition is not observed, it cannot be assumed that the same traffic will result.

It obviously cannot be taken that the single small machine is sufficient for the whole of a month whose average passengers per trip falls below six. In January the average of 3.6 passengers (say, 11 passengers for three trips) might result from one, four and six passengers per trip, or from one, one and nine, but it seems unlikely that less than two-thirds of the trips could have been made on the small type. For August with over ten passengers average nearly every trip would have to be duplicated. Working on such lines, a rough estimate of the percentage of trips which would have to be duplicated is given for each month in the third column of Table A. From these figures a new monthly mileage list can be compiled by increasing the present figures by the percentage

of duplicated trips. This gives an increase from 173,400 miles with the original fleet to 282,500 miles with the smaller machines, an increase of 63 per cent. in mileage for machines of half the original size. On a ton-mile basis, therefore, only 81.5 per cent. of the original capacity has actually been flown, and a saving of 18.5 per cent. in the running costs would be available to offset the increased cost of pilots.

As one may safely deal with averages on a curve of this type, it can be said that the average monthly cost of this service would have been reduced from the point on the curve (A) corresponding to 15,765 miles flown per month to a point above that on the line at 12,750 miles by the amount of the increased pilots' wages. The figures available suggest that for this case little or no saving would result, but it is obvious from Fig. A that on this particular fleet "standing" charges are abnormally high and a reduction in running costs produces little improvement on the total costs.

If the seasonal variation in traffic recorded in this case is typical as it appears to be on lines of this class, the possibility of increasing the load factor by nearly 25 per cent. by halving the size of machine used is well worth more thorough investigation.

It has already been said that to make a comparison in this case it must be assumed that at least the same service is given with the small machines as with the large ones, duplicating services where one small machine is inadequate for the traffic. It should be remembered that an increase in the service facilities offered will tend to increase traffic, and that if instead of duplicating the normal service (running two machines to the same schedule) during busy periods the service is doubled, i.e., only one small machine is run at a time—but services are run twice as frequently—traffic may be expected to increase.

This may be a very important factor, particularly in the case of relatively short services, and it will probably be found to place a practical limit on the economical size of machines used for such services. The most economical frequency of service is obviously a function of the time saved by air travel on a given route. For a long route—such as London-India, where air travel may save weeks as compared to the alternative route—a bi-weekly or even a weekly service may produce a reasonable traffic. But for London-Paris, where the saving is at most a few hours, several services per day are necessary to make the saving effective.

Mr. Cowley appears entirely to have overlooked this necessary connection between size of machine and possible frequency of service, together with its effect on the traffic to be expected. This is presumably because he has mainly considered the case of a long-distance route where this factor is of reduced importance. That reduced frequency of service has an effect on traffic is very well shown by Mr. Cowley's Table 2 and by Table A which I have deduced therefrom. As the monthly mileage flown falls, the average number of passengers per trip falls also; in other words, the traffic falls off much more rapidly than does the service offered. It may be said that this drop in traffic is accounted for by the decreased reliability of the service in winter rather than by its decreased frequency. It is fairly certain that both factors enter into the phenomenon and that improvement in traffic carried may be expected to result both from improved reliability and punctuality of the scheduled service and from an increase in its frequency. It is therefore unfortunate that reliability suggests the use of large multi-engined machines, whereas frequency of service calls for the smallest economical type that is available.

The inference seems obviously to be that air lines are severely handicapped on short routes where frequent services alone are likely to give paying loads, but offer much better prospects on longer services where so much time can be

saved that an infrequent service of large machines will suffice to gather the bulk of the available traffic to the air line.

A very large number of other deductions as to the commercial possibilities of air lines become apparent if the question of total cost as distinct from aeroplane costs is considered on such lines as I have here suggested, but it is scarcely possible to discuss them in anything like their full scope within the limits of a discussion of Mr. Cowley's paper.

I hope, however, that this comment will serve to direct attention to the problem of air transport economies as a whole and offset the impression which appears to be fairly general that the qualities of the aeroplane itself are the main factors to be considered.

Professor BAIRSTOW: I have had the paper too short a time to enable me to read it all through, and it seems unfair to pick out isolated points and deal only with those. I am very pleased to find that Mr. Cowley has put his views before the Society, but I am sorry that he has not made a clear distinction between the scientific and theoretical problems and the practical ones involved. It is perfectly clear that air transport is a matter of compromise from beginning to end. The best aerodynamic form of the machine depends on the cost, maintenance charges and the expenses of the headquarters staff, and so on. An aeroplane cannot be used with commercial efficiency with maximum aerodynamic efficiency since the speed required to obtain the latter is too low. From the aerodynamical point of view alone, a treatment of air transport problems is hopeless, and before its separate items can be usefully examined scientifically, some indication must be given by the operational side as to what is wanted and why.

Mr. Cowley has once more examined the effect of size of aeroplane on its weight by statistical methods following Hunsaker and others. In my opinion the particular method adopted leads nowhere, when the important correlation factors are numerous and not simple as assumed. The extraction of real information from statistics requires great care, and the usual short cuts seem to me to be highly dangerous. I should much prefer that the two sides of air transport problems should be taken separately, that the determination of maxima and minima should be made from a scientific point of view, and that the choice of the alternatives should be indicated by the operators. If the paper has done nothing else than put before us a large mass of controversial data which provokes good discussion, it will, I think, have been well worth while.

Colonel TIZARD: I agree with the previous speakers that you cannot go into detail from a purely scientific standpoint into the relative costs of the factors of air transport. You can do no more than lay down general principles to guide those dealing with air services.

I should like to see suggestions coming the other way round. The initiation of policy should come from practical men who are in a position to study commercial results exhaustively. Anyone who, like Mr. Cowley, makes a serious attempt to analyse the conditions for maximum economy in the operation of air services is greatly handicapped if he has no accurate statistics at his command. Mr. Cowley's figures of fuel cost appear to differ from other figures given to the Society. The importance of accurate figures in this respect is very great. For instance, if Mr. Cowley's figures are correct, I should deduce from them that it would be no good having your fuel for nothing if this entailed an increase of $\frac{1}{2}$ to 1 lb. per h.p. in the weight of the engine plant. Is this true, or is it not? If it is, a very definite conclusion can be drawn as to the permissible limit of weight for fuel injection engines. On a matter of policy such as this, we want an authoritative guide from the practical man—and this is still lacking.

Mr. MCKINNON WOOD: I wish to thank Mr. Cowley for an interesting and

stimulating paper. It is unfortunate that we have not had the paper in our hands long enough to go into it thoroughly. It should provoke further good discussion in writing.

Professor Bairstow has objected to the use of the statistical method to obtain the variation of structure weight with size. I think one needs to reach some opinion on this question and must use this method. I have been part author of a paper in which statistical analysis was used for this purpose. We had a scattered number of points, chiefly representing single- and two-seater aeroplanes, and one point for a really large machine. My conclusion differed from Mr. Cowley's in showing an increase of weight with size. I think his data is limited to weights under 7,000 lbs., and he exterpolates from this to draw deductions for commercial aeroplanes which range from, say, 5,000 to 30,000 lbs. There may be factors in the design of small aeroplanes which make them heavy because they are too small for it to be profitable to use material in the most economic manner.

In the same way, in his statistical treatment of engine weights, I think he is including very small, cheap engines. Moreover, the size of engines has been increasing from year to year, and if he has taken data from engines designed over a large period of years, the shape of his curve may be determined mainly by the advance of engine design.

I agree with him on the question of air- *versus* water-cooled engines that it makes little difference to the performance for speeds up to 100 m.p.h. The water-cooled engine scores heavily at speeds of 200 m.p.h.

In regard to figures 13 and 14, I had difficulty in getting Mr. Cowley's meaning. He is speaking, according to his sub-title, of the effect of varying wing area, and I think the title is misleading. I now understand that he is keeping the same engine, but allowing it to develop more power than it does in present practice, and so, keeping the same operating speed, he can increase his paying load, and he must increase his wing area to retain the same landing speed. I should like to know if this interpretation is correct.

Mr. L. T. G. Simmonds: Has the author considered the relative performance of machines which are used in this country and the tropics? It seems to raise the question of the effect of different altitudes on engine performance. Does the engine power follow the density law or the pressure law?

Mr. Hall: I would like to say that much as I appreciate Mr. Cowley's work on this subject, I agree with Professor Bairstow and Captain Sayer that there are other needs besides purely scientific investigation into possible changes in aircraft design with the object of securing economy in aerial transport.

One hot day, for instance, can put up the cost to a degree that would appear surprising to those who are not actually in touch with the operation of commercial aircraft. Such hot days as we have experienced during the past summer result in diminished lift and thrust, and these losses are often accompanied by a drop in horse-power resulting from temperature effects on carburation. Scientists could give us valuable help by tackling this problem.

Further, a spell of very hot weather denudes portions of the aerodrome of grass and bakes the surface to a brick-like hardness, and this has resulted in breakages of fuselages, and these in turn result in machines being docked for repairs at a time when our passenger and freight lists are full to overflowing.

Fuselage failures are, of course, a matter for the designers, and it is through that in some cases insufficient attention has been given to the effect of landing shocks on design, and errors in design have resulted in the aircraft ceasing to earn money for the owners and becoming the object of much expenditure on repair work—most of those present here will recollect that our fleet was at one period

during this summer almost at vanishing point, and I assure you that this was largely the result of such failures as I have indicated. It is interesting to note that these failures have ceased for the time being, partly, no doubt, as the result of reinforcement where necessary, but without doubt largely as the result of the carpet of soft ground and luxuriant grass produced by the weather of the past two months.

Regarding aircraft engines, I would say that we incline to the opinion that the air-cooled engine is best. The cost of maintenance is undoubtedly lower than that of a water-cooled engine. The first cost is also lower, and, other things being equal, the reliability should obviously be better than that of the water-cooled engine. We have at present had but little experience of these engines in commercial aviation, but we hope to be able to substantiate our opinions with the results of our first twelve months running with the air-cooled type.

I would like to add my congratulations to the Lecturer on the remarkable thoroughness of his investigation, and I am sure he will forgive me if I say that I would like to see equally thorough attention paid to the requests for help raised by those who have their time fully occupied with the task of keeping aeroplanes in the air.

Major MAYO: I congratulate the Lecturer on having condensed into such a short space such an immense subject as aircraft transport economy. It seems to me that one of the troubles we have suffered from in regard to aeronautical papers, is that the subjects chosen have sometimes been rather too wide. Nobody would attempt to write a one-hour paper on railway transport economy; to deal at all adequately with such a subject would require a book of several volumes. Aircraft transport economy is really just as big a subject, and this is shown up in the paper. The practical aspects of the various problems have had to be skimmed over because of the time limitation.

I venture to disagree with a good many of the figures given. Some of the arguments are based on obsolete figures. Starting from the first table, the type of machine considered has a performance based on theoretical figures which are not realised in practice. I do think that the application of purely theoretical figures to problems involving so many uncertain factors is very dangerous. One example of this has been referred to by Professor Bairstow with regard to multi-engined machines, where the figures for reliability are clearly misleading. In fact there is no such undulating curve as the lecturer gives us. There is no fixed percentage of engine power that is required for flying. It depends on the aero-dynamic qualities of the machine and the particular conditions under which you are flying when the engine failure occurs. The deduction that a five-engined machine is necessarily less reliable than a three-engined machine is clearly wrong, and it is not even correct to say that a twin-engined machine is less liable than a single-engined machine. There is more probability of having one engine failure, but the machine with its one remaining engine may be able to reach an aerodrome, repair the trouble in the engine that has failed, and continue its journey. It may indeed be regarded as an established fact that the twin-engine machine is more reliable than the single-engined machine. In the case of the three-engined machine, it will continue to fly on two engines and maintain its height. It will prolong its glide to a very great extent on one engine alone, so that its actual reliability under normal loading conditions is practically 100 per cent., and the same thing will apply to most machines with three engines or more.

With regard to possible improvements in the stream-lining of the fuselage, it is not possible, having regard to the requirements of commercial machines, to design a perfectly streamlined machine. You have got to provide a fuselage of large cross section to take the passengers. The pilot, and assistant pilot, must be able to see. You have got to carry certain equipment which you cannot tuck inside the fuselage. Therefore the designer is limited. Some improvements on the

present types can no doubt be made, but it is not possible to make a theoretically perfect machine that is suitable for commercial work.

With regard to the resistance offered by air-cooled engines, Mr. Cowley has based the whole of his argument on tests carried out upon the "Weasel" machine, a small two-seater machine with a large diameter air-cooled engine, the cylinders of which stuck right out of the lines of the fuselage. That does not adequately represent the problem with which we are faced in commercial machines. Fuselages of very large cross-section are now employed. The relationship between the air-cooled and water-cooled engine—where the engine becomes of small diameter in relation to the fuselage behind it—may be quite different, and the general deduction that the air-cooled engine necessarily gives much greater body resistance may be wrong.

I congratulate the Lecturer on having provided a great deal of interesting material, and hope that there will be further discussion of it in the Journal.

Mr. R. J. Goodman Crouch (*Communicated*): I should like to congratulate Mr. Cowley on his well thought out contribution to the economics of air transport. In modern times the first question which is asked about a project is "will it pay?" and no business can ultimately survive except on a sound commercial basis. Theoretical investigations into the economics of a project necessarily have their limitations, but the present paper details the problems to be solved and indicates methods for their solution in a manner which will permit of adjustment of viewpoint under the various heads without invalidating the logic of the author's presentation of the factors.

At present our experience is limited to comparatively few air routes operating in Europe and America, and data is accordingly meagre. The project of an air line to India, however, offers such undoubted advantages over existing forms of transport that the solution of the engineering and operational problems presented is a challenge of absorbing interest to all believers in civil aviation. They will welcome Mr. Cowley's paper accordingly as an outstanding contribution to the solution of these problems along scientific lines.

Mr. Cowley has endeavoured to assess the economic cost of reliability. Reliability is one of those items which appears on both sides of a balance sheet; on the one side admittedly as an expenditure, but on the other as a credit item, a small part of which can be assessed in cold figures as, for example, a reduction in insurance rates, but the major portion of which is of vital importance, though less amenable to treatment by auditors' methods. I refer to goodwill which may, in the case of an aircraft operating company, be expressed as the belief by their clientèle in the absolute reliability of the service they are offered. Upon this reliability consistently proved year in, year out, by the operating companies, depends the passengers' morale, which covers a gradation of feeling ranging from fear of a serious accident to apprehension as to missing a business appointment.

From a strictly commercial aspect, therefore, based only on the admission of goodwill as a business asset, strict attention to every safety consideration and, second only to these, due attention to every item that can further contribute to reliability, cannot be too strongly advocated.

One of the features of the paper is the author's dissection into a very large number of variables, the considerations that affect the operation of civil aircraft. I would like to make a few comments on three of these variables, namely, machine size, power plant reliability, and the question of optimum flight stage.

There would appear to be a definite trend in the direction of the large machine; this involves multiple power units and brings in its train a distinct gain from the structural viewpoint in the ability to distribute the engine and fuel loads over the supporting surfaces, thus relieving the wing loadings and reducing the structure weight. The large machine, too, favours all metal construction with its

attendant advantages, among which must be included stability of condition under climatic changes.

As to power plant reliability, the author has dealt with the merits and demerits of the water-cooled engine; it must, of course, be agreed that on general grounds the elimination of components such as radiators, water pumps and other organs of the cooling system should operate in the direction of an increase in reliability. In practice, however, it would seem doubtful whether more can be said than that in the side-by-side evolution of water-cooled and air-cooled engines, the latter has at the moment a trend towards supremacy.

I should like to congratulate the author upon his particularly lucid treatment of the question of optimum flight stage. This is a factor of the greatest importance, and one to which, in the past, due attention has not always been given. It is essentially not a question which can be dealt with on theoretical grounds alone, but, on the contrary, one which requires to be the subject of a joint report by an engineering and a traffic expert after detailed examination of the route and possible alternative routes. As in other transport undertakings, engineering and traffic considerations will sometimes be conflicting, and the most economical course will as a result take the form of a compromise. It is considered to be of the very greatest importance to obtain technical advice on this point, while the air line is still in the project stage, and not after the expenditure of capital on aerodromes and their equipment has made a change economically impossible.

In conclusion, I should like to make a few remarks as to the commercial cost of civil aircraft. Here we are immediately faced with conflict between the two fundamentally opposed policies of development and standardisation respectively. A freedom to develop types each of which is successively an improvement on its predecessor as a fare or freight earning vehicle, must lead to a state of affairs which, in the extreme, will end in the company owning a fleet of dissimilar machines, the latest of which is no doubt highly efficient for its purpose, but the sum of which, together with their associated heavy oncosts for individual spares, presents an aspect which is economically deplorable. The extreme converse offers the advantage of standardised machines and spares, but leads to a fleet of machines which will, from the day of their building, enter the stage of obsolescence. A middle course has already been taken in standardising a type and operating the machine for an economically assessed period, and regarding this period as the useful life, but there remains an alternative policy. The development of all-metal aircraft, especially in certain directions, will definitely permit of the interchangeability of units and components, or alternatively a specialised process for their repair on site to an extent which offers invaluable advantages.

Suitably developed, these features may very well lead to such interchangeability as will bring about many of the advantages of standardisation, without the attendant disadvantage of stagnancy of development.

Mr. J. L. NAYLER (*Communicated*): I regret very much that I am not able at the last moment to be present when Mr. Cowley is reading his paper on Air Transport Economy, especially as I have been in close touch with his work on this subject since its commencement. I think he has been attacking a most difficult problem with data totally inadequate, due to the short time that civil aviation has been in being, and yet he has been able to suggest, as the result of his work, a number of directions in which progress can be assured. It has also been difficult for Mr. Cowley to know how far he may consider the practical limitations of the problem to be elastic or otherwise.

Since Mr. Cowley commenced his work, there have been before the Society two, at least, excellent papers on the same subject, one by Sir Sefton Brancker, read very recently, and the other by Mr. Tizard during the last session. To both of these I think the present paper has a bearing.

Mr. Tizard has suggested that body drag is an important factor, and I should like to ask Mr. Cowley what estimated improvement would result if (say) the body drag at cruising speed of some present-day civil aeroplane were reduced by half, while carrying the same weight and using the same horse-power. I am afraid this may be a difficult question to answer.

Mr. Cowley has drawn attention to the effect of varying wing area. I should like to ask how much of his estimated improvement is due to increase of area and how much to aspect ratio.

Mr. Cowley also draws attention to the fact that statistics on the weights of aeroplane structures indicate that an increase in machine size is conducive to greater economic efficiency, and if this problem is as important as Mr. Cowley suggests, it is to be hoped that someone will work on it, paying attention not only to single-engine machines, but to the three-engine machines with their greatly improved reliability as compared with the single engine.

It would be interesting to know how a seaplane or an amphibian would compare with the aeroplanes on which Mr. Cowley has concentrated his attention, and if he has made any calculations on the subject. I am sure such calculations would we welcomed in view of their probable usefulness for British routes to the East, where harbours are possibly easier to find than aerodromes, and cheaper to maintain.

Quite recently many have seen the Cierva autogyro fly, and heard the inventor describe its qualities before the Society. As this type of flying machine lands with such a phenomenally short run, I should be glad to know whether Mr. Cowley would tell us if he considers it an economical machine for air transport, using as a basis the same analysis as in the paper he has read.

Sir SEFTON BRANCKER : I think that you will agree with me that Mr. Cowley has undertaken a colossal task ; in doing so he has suffered from the fact that the only official figures available are almost four years old. We have learned a good deal since then, and if a similar estimate were made now, many details would be altered ; for instance, the fleet would be smaller and the number of spare engines greater.

Major Mayo said that the paper was based on the performances of an aircraft which did not exist and had never existed. As a matter of fact, the figures were given just at the time when the D.H.34 had begun to fly and they represented the performance of an improved D.H.34, possibly fitted with slots or flaps.

Although Mr. Cowley carried out his arguments on these old figures, he has arrived at results which are accepted in practice to-day. For instance, he mentions that the economic stage should be somewhere about 250 miles, and that the economic cruising speed is 95 miles an hour.

In my discussions with Colonel Burchall regarding the Cairo-Karachi service, we arrived at the conclusion that 250 miles was about the right economic stage for this service. The cross-Channel services have proved that 95 miles an hour is about the right economic speed for the carriage of passengers and mails.

Mr. Cowley's statement that 95 miles an hour will also be an economic cruising speed for a freight-carrying machine certainly surprises me. We should be in a position to prove or disprove this contention in the future ; the Air Ministry are ordering an experimental freight-carrying machine for which we are demanding the slowest possible speed, perhaps about 65 miles an hour, in order to carry as great a load as possible.

With regard to aircraft employed in the tropics, I am beginning to think that we shall have to produce special designs for tropical work—designs with special propellers, different angles of incidence, and perhaps even different wing section. To-day we are employing machines designed for European conditions in the East. I feel that by doing so we are really not getting the best out of

our engines. The new route which we hope to start from Cairo to Karachi will give us an excellent opportunity for studying the problems involved.

I congratulate the lecturer on the hard work and intelligence he has applied to this elusive problem. As a fellow-member of his on the Air Transport Sub-Committee, I would urge all operators to let us know the lines of research which they think should be undertaken towards solving the vital problem of providing a really commercial aircraft, *i.e.*, an aircraft which can fly without being bolstered up financially by the Government. I would suggest that everyone who has made comments to-day, and also those who have not, should read the paper carefully and let Mr. Cowley have their further queries and comments through the Secretary of the Society. I know he will be very glad to answer these, and I hope that they will lead to a useful discussion in the Journal.

REPLY TO DISCUSSION.

Mr. COWLEY: I am very interested in Captain Sayers' remarks, and hope he will develop his work. Captain Sayers misunderstood me, however, when he stated that I have assumed the traffic to be proportional to the capacity of the machine. Apparently, I have not made my position clear in the paper. It may be regarded that my treatment is equivalent to such comparisons as where, in one case, two machines leave the terminal aerodrome daily at 11 a.m., and in the other case, where one machine only is used carrying a load equal to the sum of the loads for the other two. In this way the difficult question of the effect on economy of variations in the timetable does not enter. I admit that an increase in the size of the machine will, in general, lead to alterations in the timetable, but each case must be treated on its own merits. The whole question is very complicated, and no attempt to study it has been made in the paper.

I agree with the remarks of Professor Bairstow and Mr. Tizard, except that I would not go so far as to say that statistical work leads one nowhere. Many designers use these methods, and although they would agree that the position is not altogether satisfactory, they frequently find themselves with no alternative.

On the question of reliability, although I have assumed that one-third of the horse-power is available for climb, allowance can easily be made in the formulæ given for any deviation from this value which may occur. The value of one-third is the figure I have deducted for economically efficient machines of the present day, and although conditions might and most probably will alter, I do not think there are any marked indications that this figure will undergo much change in the near future.

I thank Mr. Tizard for pointing out one valuable point in Table 1, viz., the table indicates that it would not be an economic advantage if you received your fuel for nothing provided that by so doing you add 1 lb. per b.h.p. to the weight of your engine.

Mr. McKinnon Wood has pointed out that the variation in the engine weight per horse-power with engine power shown in Fig. 6 may be due to a time effect, thus the higher-powered engines might be more modern productions and consequently the engines would be lighter as the designers of those engines have the advantage of more recent knowledge. I cannot deny the possibility of a time factor, but some of the lower-powered engines are fairly modern. The engines selected by me are taken from those accepted by the Air Ministry for airworthy engines, and their dates of construction do not extend over a very long period. The dates of construction for some of the engines marked on the diagram were 1918 for the Napier Lion (425 h.p., 2.17 lb./b.h.p.), 1921-22 for the Bristol Cherub (18 h.p., 4.16 lb./b.h.p.), and 1921-22 for the Siddeley

Lynx (190 h.p., 2.62 lb. b.h.p.). In these cases the time factor is in the opposite direction to that suggested by Mr. McKinnon Wood.

The effect of tropical temperature upon performance of aeroplanes is under consideration by the Air Transport Sub-Committee, and many interesting problems are arising out of the work. As pointed out by Mr. Simmonds, the effect upon the aeroplane performance will depend upon the variation of engine power with inlet air temperature, that is, upon whether the engine power varies according to the density or the pressure of the atmosphere. As far as I can see at present, no definite decision upon this question has been arrived at by engine experts. The latest work to date is that carried out in America in an altitude chamber (see Report No. 190, N.A.C.A., "Correcting horse-power measurements to a standard temperature," by Stanwood W. Sparrow). These tests appear to indicate that the power is proportional to the air pressure divided by the square root of the absolute temperature of the air.

It is very helpful to get the views of Mr. Hall, who has had considerable experience in the commercial operation of air lines. As regards the first problem pointed out by Mr. Hall, viz., the effect of air temperature upon machine performance, I should like to say that questions embracing this problem have been raised before the Air Transport Sub-Committee and are still receiving attention. Under these circumstances I am not able to include this work in my paper. The second point mentioned, viz., the structure failures during landing, represents a type of problem that I consider is a little outside the range of my subject. In mapping out the scope of the paper I decided to confine my attention almost entirely to problems based upon present conditions. Thus machines are supposed to operate in the usual manner and take off and land on ordinary aerodromes.

Mr. Hall raises a very controversial subject when he stresses the relative importance of the various problems, because different problems are given varying degrees of importance by the several experts.

I beg to thank Major Mayo for congratulating me on having achieved something which was never attempted.

Really his first remarks are objections to the title of the paper. The Council asked me if I would read a paper on "Aircraft Transport Economy." A paper covering the whole subject would have been unmanageable, so I decided to take the standpoint, to which objection has been raised, shown in the paper.

With regard to the reliability of machines, I understand reliability to mean working to a definite timetable. Apparently Major Mayo understands reliability to mean the completion of the journey irrespective of time. Under this hypothesis the Southern Railway is absolutely reliable.

In the comparison of air- and water-cooled engines, I showed that, using the available full scale data, there was no difference aerodynamically, whereas available wind tunnel work favours the water-cooled engine. Whether recent or future modifications will produce any variation from this result remains to be proved. The question as to whether any particular Company does or does not use nose radiators is quite irrelevant.

I wish to thank Mr. Goodman Crouch for his well-thought-out and very interesting contribution to the discussion, and to state my complete agreement with the views expressed therein.

In reply to Mr. Nayler's first question, if the engine size and the commercial load remain unaltered, the economic gain will be relatively small, as it would only amount to the saving in the fuel bill due to a smaller petrol consumption resulting from using the engine at lower power during cruising. Considerable gain would undoubtedly result, however, if the machine were re-designed—for example, if it were made to carry a greater load.

In my paper I have not considered the effect of varying the aspect ratio of the wings. This problem involves questions of structure design that are very difficult to investigate satisfactorily.

I have not made calculations upon the economy of seaplanes or amphibian machines. The design of such craft is making great progress at the present time, and although a year or two ago these machines were economically inferior to the aeroplane, the difference now is not so marked and it is highly probable that they would be superior to aeroplanes over long coastal routes.

It is rather early in the day to forecast the commercial future of the Cierva Autogyro. Professor Bairstow, in the discussion at Senor de la Cierva's lecture, gave one very good reason for expecting that the performance of this machine would in general be inferior to that of the orthodox machine, apart from its lower landing speed. Conditions may alter with time, however, and it has not yet been established whether or not aerodynamic efficiency would result from advantages such as the possibility of using wings of higher aspect ratio on the autogyro than on the orthodox machine. For these reasons I feel that it would be rather rash to forecast.

EVAPORATIVE COOLING OF AERO ENGINES

(*Note on Lecture by Wing Commander T. R. Cave-Browne-Cave, published in the* JOURNAL *for January*, 1926.)

Mr. E. B. Wood (Member of the Institution of Automobile Engineers) has drawn attention to a system of internal cylinder cooling described by Hopkinson (*Proc. Inst. Mechanical Engineers*, 1913, Vol. II.). The system has a disadvantage in the quantity of water lost, but this would be avoided if water recovery apparatus were in use.

Water was injected into the cylinder from 30 degrees before to 30 degrees after the explosion "in centre." The jets were directed on to the exhaust valve and on to the piston and non-rubbing portion of the cylinder.

The system worked very satisfactorily with horizontal gas engine cylinders, including one of 1,000 h.p. with opposed pistons, but was never applied to a vertical cylinder for fear of the deposit of solids on the working surfaces. The deposits would largely be avoided if water condensed from the exhaust were employed, but there would be an increasing concentration of acid in the water which might cause corrosion.

Hopkinson found that the consumption of water was 2.5 lbs./b.h.p. hour. This would increase the quantity of water in the exhaust gas of 1 lb. of fuel from 1.17 lbs. to 7.17 lbs., and is sufficient to cause condensation to begin at 80 degrees or 90 degrees C. This might facilitate the deposit of unburnt fuel and thereby leave the low temperature part of the cooling surface comparatively clear, but it has the disadvantage that the temperature of the exhaust gas is considerably reduced, although its heat content is not reduced. The efficiency of the high temperature end of the cooling apparatus will therefore be reduced, because much of the heat which is now easily dissipated at a very high temperature would have to be discharged at lower temperature, therefore requiring greater surface.

The proposal is an interesting one, but the potential advantage does not appear sufficient to justify, under the present circumstances, experiments with the application of the internal system of cooling to a vertical high-speed engine.

February 10th, 1926. **T. R. CAVE-BROWNE-CAVE.**

RÉSUMÉ OF TECHNICAL INFORMATION

Compiled by the Directorate of Technical Development (R.T.P.), Adastral House, Kingsway, London, W.C.2.

AERODYNAMICS

U.S.A.

Preliminary Wing Model Tests in the Variable Density Wind Tunnel of the National Advisory Committee for Aeronautics. N.A.C.A. Report No. 217. (11225.)

This report contains the results of a series of tests with three wing models. By changing the section of one of the models and painting the surface of another, the number of models tested was increased to five. The tests were made in order to obtain some general information on the air forces on wing sections at a high Reynolds Number, and in particular to make sure that the Reynolds Number is really the important factor, and not other things like the roughness of the surface and the sharpness of the trailing edge.

The few tests described seem to indicate that the air forces at a high Reynolds Number are not equivalent to respective air forces at a low Reynolds Number (as in an ordinary atmospheric wind tunnel). The drag appears smaller at a high Reynolds Number and the maximum lift is increased in some cases. The roughness of the surface and the sharpness of the trailing edge do not materially change the results, so that confidence is felt that tests with a systematic series of different wing sections will bring consistent results, important and highly useful to the designer.

The Report No. 217, which is by Max M. Munk, may be obtained upon request from the National Advisory Committee for Aeronautics, Washington, D.C.

AIRCRAFT

Holland

New Fokker Aircraft built by Romeo Co. La Gazetta dell'Aviazione, November 23rd, 1925. (21225.)

A new Fokker aircraft, built at the Romeo Works at Naples, is shortly to undergo its flight tests.

The aeroplane is of entirely new design, having a new wing profile, an engine bed permitting of interchangeability of the engine airscrew unit, and an interchangeable wing unit.

This Fokker aircraft is intended for reconnaissance and light bombing, and will be fitted with a 500 h.p. engine.

Italy

The Ansaldo A.115 Reconnaissance Aeroplane. L'Ala d'Italia. October, 1925. (31225.)

This aircraft is constructed entirely of wood, except for the engine bed, which is built up of high strength steel tubing and attached to the fuselage by four bolts. The engine is a 400 h.p. Lorraine, but this can easily be replaced by a 450 h.p. Lorraine or various other engines. The forward part of the fuselage is covered with duralumin and can be easily dismantled to give access to the engine. The remainder of the fuselage is built up of plywood frames with spruce

and ash longerons, wooden cross-members and steel cables. The covering is of plywood.

The wing unit is biplane, the top wing being considerably larger than the bottom wing. The interplane struts are of steel tubing.

The undercarriage is of round steel tubing suitably streamlined, and the tail is of wood, fabric covered.

The aeroplane has a camera and W/T set, and is fitted with a Vickers machine gun firing through the airscrew, and a Lewis gun on a turret actuated by the observer. The camera can be replaced by a bomb or bomb gear.

Twin-Engined Breda Aircraft to Undergo Tests. La Gazetta dell'Aviazione, November 23rd, 1925. (41225.)

This aircraft will shortly undergo the flight tests for the night-bomber competition. The top wing is slightly larger than the bottom wing, and the tail is of the biplane type. There are two 400 h.p. Lorraine engines installed, mounted laterally.

The useful load of the aircraft is 3,970 lb.

New Teichfuss Glider. La Gazetta dell'Aviazione, November 5th, 1925. (51225.)

A new glider, of the parasol type, suitable for training purposes, has been built by Sig. Teichfuss, of Bologna.

The fuselage is built up entirely of steel tubing, the cockpit being lined with plywood. The wing, which has the Gottingen No. 441 profile, is made in three parts, and has large ailerons controlled by steel tubes. The elevator is controlled in the same way, and the rudder is pedal-controlled.

The glider lands on a large central skid fitted with a pneumatic shock-absorber.

The principal characteristics are as follows:—Wing span, 34ft. 9in.; wing chord, 4ft. 5in.; wing thickness, 7in.; overall length, 14ft. 9in.; total weight, 260 lb.

Russia

The Sedelnikoff Light Aeroplane. Viestruk Vozdushnavo Flotta, October, 1925. (61225.)

This aircraft, which was designed by an engineer named Sedelnikoff, is being constructed at the Krasni Letchek Factory, Leningrad.

It is designed as a two-seater and is to be fitted with a motor-cycle engine. The ceiling, with 18 h.p. engine, and two passengers, is 6,560 feet.

New Soviet Aeroplane. Viestruk Vozdushnavo Flotta, October, 1925. (71225.)

This aircraft is a passenger monoplane designed for use on the Russian lines as a small load carrier.

The wing is covered with fabric, and is original in form, being a rounded ellipse. The engine and engine bed can be removed integrally from the fuselage.

The following characteristics are given:—Engine, Salmson 160 h.p.; cruising speed, 81 m.p.h. (approx.); endurance, 2½ hours; ceiling, 8,200 feet; climb to 3,280 feet, 12 minutes; wing profile, Prandtl No. 436.

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REVIEWS

With Seaplane and Sledge in the Arctic

By George Binney.

This is a good story, simply told, of the fine efforts of twenty-one young Britishers, who cheerfully carried out valuable pioneering work in Arctic exploration under great difficulties. Work of this nature always involves risks to life and limb and these risks were taken as part of the day's routine. That hardship and disaster was avoided was undoubtedly due to Mr. Binney's very practical handling of the expedition, his choice of personnel, and last, but not least, to a kindly Providence. Mr. Binney obviously made good use of the experience which he gained on the two previous expeditions, and the 1924 expedition was fortunate in having such a leader.

It is only proposed in this short review to touch on the flying side of the expedition as related in Mr. Binney's book. The advent of aviation provides an additional reason for exploring the Polar regions and lends added interest to the valuable work carried out by the Oxford University Arctic Expedition. Owing to the considerable saving in distance, it may well be that certain air routes of the future will pass across the North Polar regions, two outstanding routes being England to Vancouver and England to Japan. North-East Land, which forms part of Spitzbergen, was the area in which the Oxford Arctic Expedition carried out their operations. It is somewhat to the north of the air routes referred to, but the fact that Spitzbergen has clear water in spite of its high latitude, due to the effects of the Gulf Stream, may well warrant the establishment of an aircraft base there which, although slightly off the route, would have the advantage of being in direct shipping touch with the rest of the world. The fact that coal deposits are worked in Spitzbergen should also be a contributory reason for forming a base there.

Mr. Binney's book is obviously written for the man-in-the-street. He makes no attempt to deal with the scientific aspect of the work and rightly leaves this to the papers which the various experts concerned with the expedition have prepared. Anyone contemplating an Arctic expedition is bound to acquire considerable information by reading the book, while as a record of achievement and of British enterprise the book ranks high and should find a place in every library in the country. In certain parts the author appears to show a lack of the relative values of the work carried out, but this is probably due to the spirit in which the book was written.

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